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LIQUID METAL MAGNETOHYDRODYNAMICS

(LMMHD)

TECHNOLOGY TRANSFER

FEASIBILITY STUDY

VOL. II: APPENDIXES

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APPENDIX A

ELECTRICAL POWER GENERATION REQUIREMENTS AND BACKGROUND

A. INTRODUCTION

Our society is expressing an increasing awareness and concern over the implications of emerging limitations in energy resources, and the current and potential environmental impact of fossil fuel and nuclear energy conversion technologies. Additionally, our Nations's ever-increasing demand for electrical power in virtually every aspect of energy use has led to an attractive market for new, more efficient methods of power generation.

To meet the needs of new projected electric power generation capacity in a timely manner, an analysis of power system requirements is necessary. Generation alternatives must be considered in terms of cost, public acceptance, and environmental impact, based upon current state-of-the-art and anticipated near-term advancements in component performance and technology developments. In supporting the selection of the most-favorable or least-impacting alternative, an adequate source of baseline data is required.

In order to provide an adequate basis for comparison of candidate alternate systems with LMMHD and to provide background information for the reader who is not closely associated with the power field, a review of potential utility power generation requirements and characteristics was conducted. Requirements and characteristics were defined in terms of energy requirements and electrical load characteristics. In addition, background information is provided as a foundation for the study.

In developing background information it was recognized that there is a need for a national power policy, site selection procedures, intensified research and development, satisfaction of environmental standards, meeting of financial obligations, while providing adequate quality service. Topics sketched briefly here include: the structure of the industry, number and size of plants, environmental restrictions, siting constraints, financing, and research and development needs and trends. In providing background information it is recognized that the electrical power field is a vast subject which cannot be described adequately in a study of this type; and no attempt is made to do so. Instead, sufficient information is provided so that the study can proceed with the evaluation of the LMMHD topping cycle system.

B. ENERGY REQUIREMENTS

Energy consumption in the United States is predicted to continue to increase dramatically. Electrical power consumption is estimated to increase even more rapidly than the total energy consumption. This fact indicates the need to consider the application of new power generation alternatives so that material resources can be preserved, the environment protected and reasonable power costs achieved.

To provide a basis for comparing LMMHD with other alternatives for producing future electrical power, predicted energy and power requirements have been accumulated from various references and summarized in this section. Also included are predictions of the types of plants and fuel to be used. This will enable prediction of the impact any advanced systems will have on the total power generation.

There have been several predictions of energy consumption (Refs. A-1 to A-4). References A-1 and A-2 present annual increases in total energy demand of 3.5% and 4.2%, respectively. Specific U.S. energy consumption projections from Reference A-1 are as given in Table A-1.

The annual electrical energy demand rate of increase has been estimated in Refs. A-1 to A-4 to vary between 6% and 8%. Figure A-1, from Ref. A-4, shows a prediction of the electric utility energy requirements. The U.S. electrical power generation demand is shown in Fig. A-2 for the various types of power plants. This prediction is from Ref. A-1 and is in fairly good agreement with the projections shown in Fig. A-1. The breakdown of the fossil fuels

Table A-1. U.S. Energy consumption projection (Ref. A-1)

Year	Total Consumption (Quadrillion BTU)
1970	68.8
1975	88.6
1985	133.4
2000	191.6

shown in Fig. A-2 is extracted from data from Ref. A-4 which also describes the factors influencing the rapid growth projections in electrical energy from nuclear sources.

Reference A-1 projects the requirements for fossil fuels as shown in Table A-2. These projections are based on forecasts by the Federal Power Commission and the Atomic Energy Commission. They consider the fact that utilities no longer rely only on the most economical fuel, but take into account factors such as

1) Environmental restrictions.
2) The short supply of natural gas.
3) The limited development of coal mining due to several factors such as the prospect of nuclear energy growth and more stringent health laws.
4) Decreased availability of domestic oil.
5) Decreased availability of refinery products.

Nuclear generating capacity has also been predicted in Ref. A-1 for various types of plants as shown in Table A-3. It shows the dominant position to be taken by breeder reactors during the latter part of the century. This LMMHD applications study considers primarily the period through 1990, during which time the breeder reactors will play only a minor role.

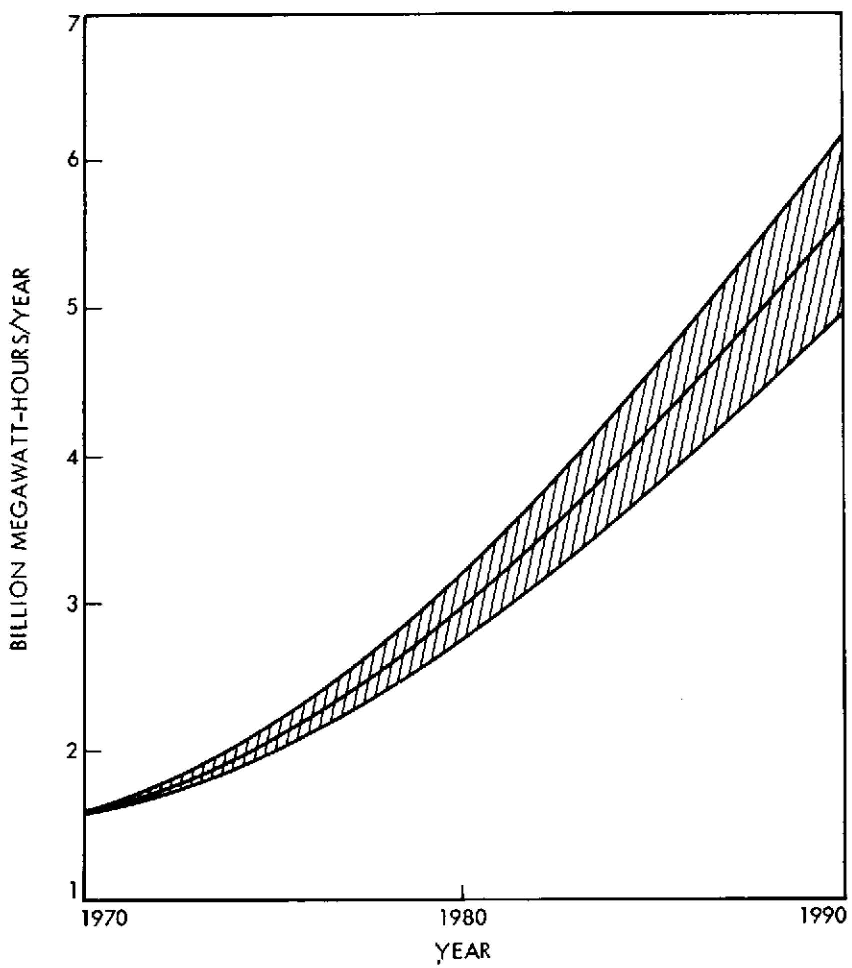

Fig. A-1. Electrical energy requirement (Ref. A-4)

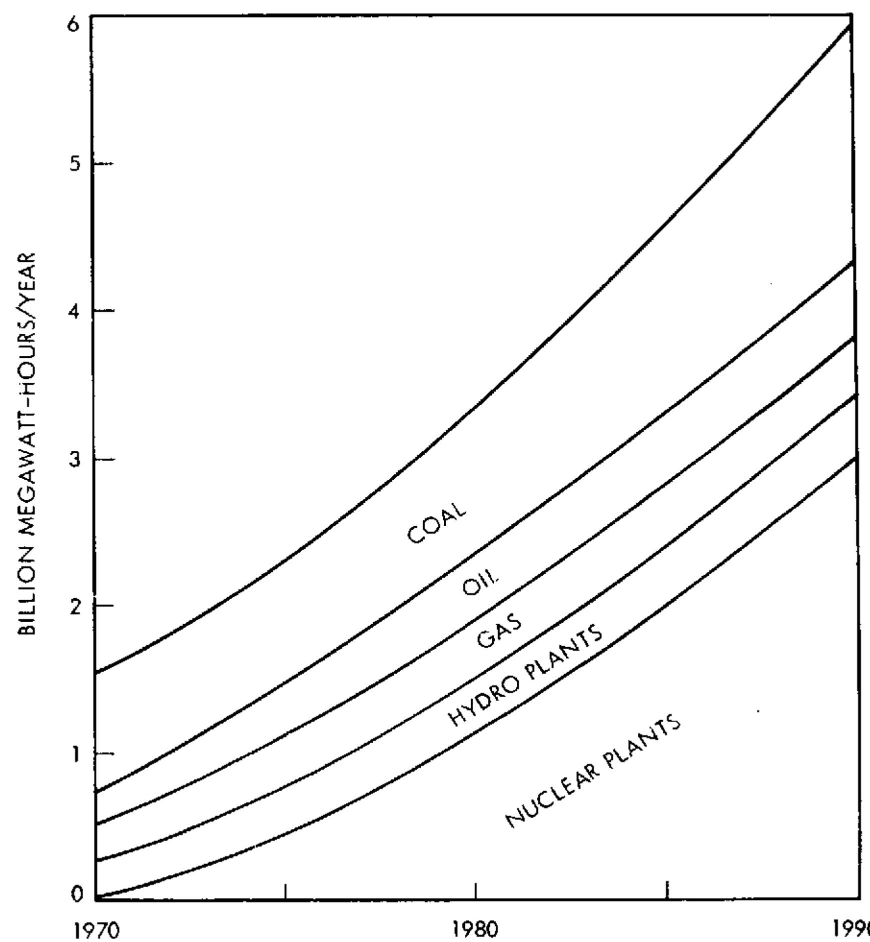

Fig. A-2. U.S. Electric power generation demand (Refs. A-1 and A-4)

Table A-2. Electrical energy fossil fuel requirements (Ref. A-1)

Fuel	Year			
	1970	1975	1985	2000
Coal:				
Millions of tons	326	407	535	680
Trillions of BTU	7, 824	9, 750	12, 800	18, 720
Oil:				
Millions of barrels	362	400	450	140
Trillion BTU	2, 263	2, 520	2, 830	880
Natural Gas:				
Trillion cubic feet	3. 9	4. 0	4. 2	4. 0
Trillion BTU	4, 025	4, 130	4, 340	4, 130

Table A-3. Nuclear generating capacity (Ref. A-1)
(Thousands of Megawatts)

Nuclear Plant Type				
Year	LWR*	HTGR**	Breeders	Total
1970	7	---	---	7
1980	145	3	---	148
1990	371	62	14	447
2000	348***	181	374	903

*LWR = Light Water Reactor.

**HTGR = High Temperature Gas-Cooled Reactor.

***The decrease from 1990 is not explained in Ref. A-1. The lifetime of the LWR plants would probably permit equivalent production in the year 2000 or in 1990; however, LWR's may be phased out in favor of breeders to conserve fuel.

United States fuel mineral requirements and resources for the 1970-1985 period were summarized in Ref. A-1, and repeated here in Table A-4. Note the difference between requirements and known reserves for petroleum, natural gas and uranium. This difference between requirements and known reserves is the basis for the predicted growing energy crisis. Even the additional potential economic resources are not large. Additional submarginal resources are substantial, but the capability to utilize them is uncertain.

C. ELECTRICAL LOAD CHARACTERISTICS

Wide variations in daily and seasonal electric loads result from differing energy consumptions by commercial, residential and industrial customers and their different cycles of need. These variations, in turn, result in different types of plants having different load and start-up requirements. Some information is presented here illustrating electrical load characteristics to aid in defining the prefered applications of LMMHD.

System loads peak during week days and fall off during weekends. Diurnal peaks are typically achieved during midday. Daily loads have changed recently, however, due to increased use of air conditioning in the summer and space heating in the winter. Typical weekly and monthly patterns of electrical loads are shown in Figs. A-3 and A-4 from Ref. A-4. Note the daily peak loads in Fig. A-3 and the seasonal peak loads in Fig. A-4. In Fig. A-4 the South Central region peak load is in the summer, whereas the West region has a more even load distribution with smaller peaks in summer and winter.

This varying load requirement results in the need for three types of plant operation (see Fig. A-3):

1) Base load plants.
2) Swing plants.
3) Peaking plants.

Base load plants operate at full capacity at all times; swing plants operate at all times under varying load conditions; and peaking plants operate intermittently to meet peak load requirements. Because the LMMHD system is difficult to stop and start, it is most applicable to base loading plants. It is

Table A-4. United States fuel mineral requirements and resources (Ref. A-1)
1970 - 1985 (Cumulative)

Item	Requirement*	Known Reserves*	Additional Potential Economic Resources*	Additional Submarginal Resources*
1. Petroleum Liquids (Crude oil and natural gas liquids)	0.65	0.26	2.7	14.0**
2. Natural gas	0.45	0.30	2.1	4.5**
3. Coal	0.27	4.80	3.0	25.0
4. Uranium	0.20	0.17	0.43	475.0
5. Oil shale	--	--	--	80.0
6. Thorium	--	--	--	550.0

*Data expressed in units, times 10^{18} BTU.
**Includes an estimate for the U.S. continental slope.

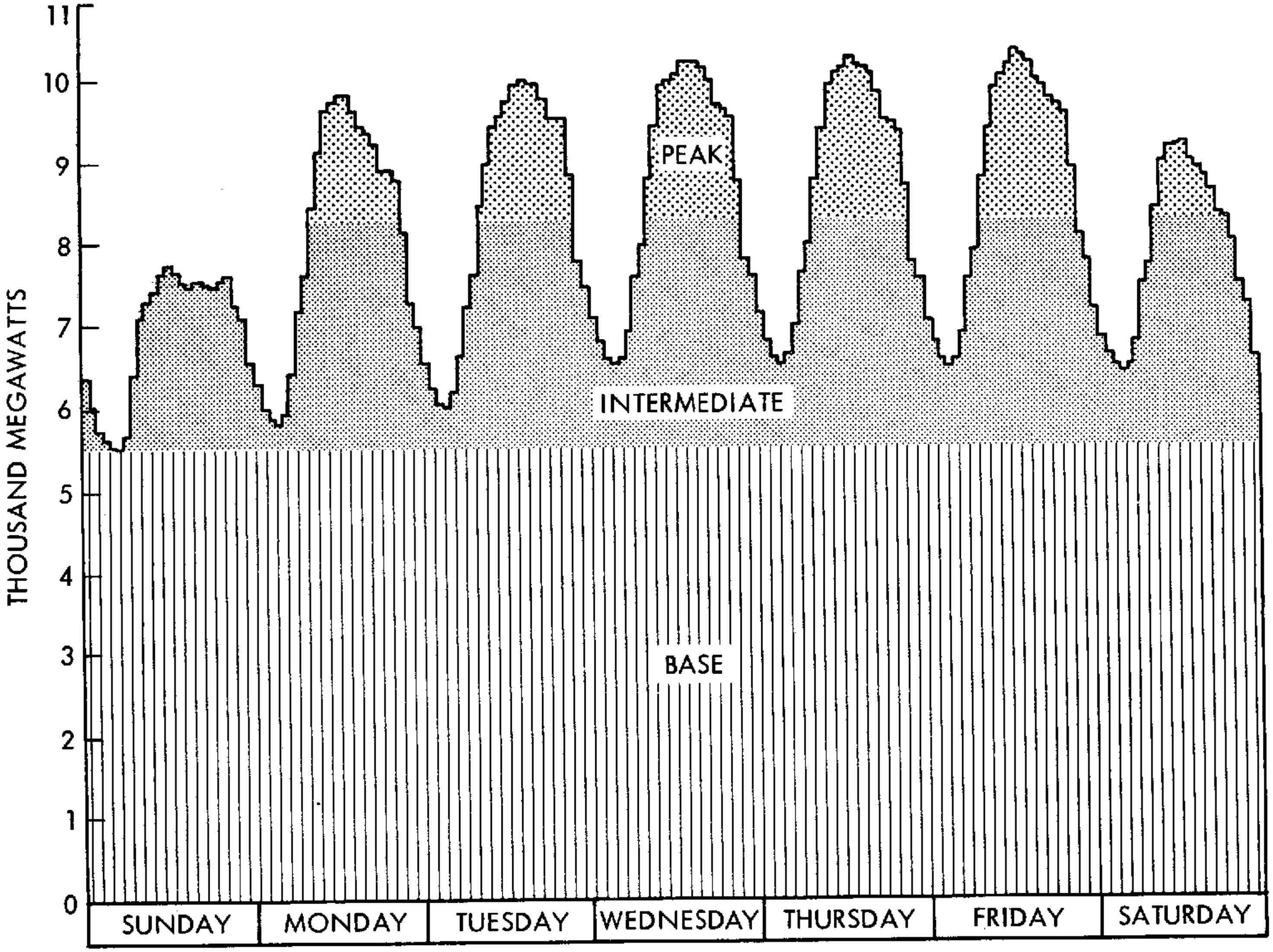

Fig. A-3. Weekly load curve (Ref. A-4)

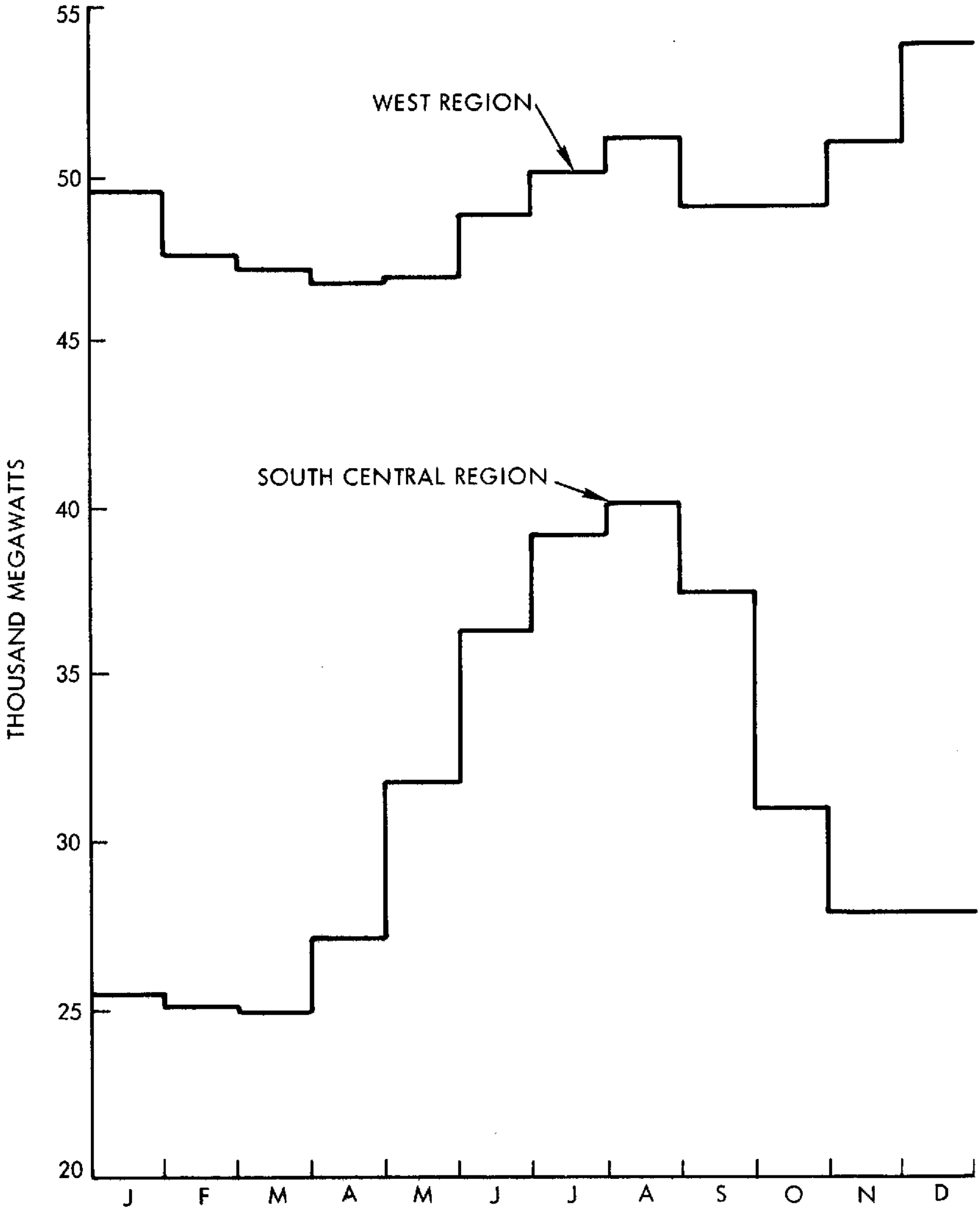

Fig. A-4. Estimated 1970 monthly peak demands (Ref. A-4) possible to follow load variations with an LMMHD/steam plant; thus, the system could also be applied as a swing plant.

D. STRUCTURE OF THE INDUSTRY

Developers of new technology for the utility industry need to understand the structure of that industry to effectively infuse it with their technology improvements. The electrical utility industry in the United States includes 3500 systems of varying size, range of function and type of ownership. The ownership includes investor-owned companies, non-Federal public (local government-operated) companies, cooperatives and Federal agencies as follows (Ref. A-4).

Ownership	No. of Systems (1968)	% Power Generated
• Investor-owned	405	77
• Public Non-Federal	2075	11
• Rural Electrification Administration Cooperatives	560	1
• Federal	5	11

This unique and diverse system has large systems which provide all functions, i.e., generation, transmission and distribution, as well as smaller organizations which provide only distribution.

Trends in the industrial structure are the following. The number of investor-owned companies are declining as are public-owned non-Federal systems to a lesser degree. With the total number of systems declining, the trend is toward larger and fewer electrical generation organizations to meet the challenges of electrical growth requirements and technological advances. At the same time there is an increase in the number of organizations involved in distribution only. This indicates a general trend toward concentration in electrical generation, while distribution, customer service, and marketing may continue to be provided by separate, smaller, decentralized companies. Manufacturers which provide the utility companies with components and systems have typically taken the lead in providing product improvement. There is a trend, however, with the formation of the Electric Power Research Institute, for power companies to combine their resources to provide for system improvement.

E. SIZE AND NUMBER OF PLANTS

Projected plant size must be known to form the basis for comparing LMMHD with other candidate systems. Also, the projected number and type of plants is required to estimate amortized research and development costs and potential future cost savings for advanced systems. The projected size and numbers of plants is given as follows. The power generation mix by various energy sources was shown in Fig. A-2. The increasing dependence on nuclear energy sources is apparent, although fossil fuel sources, particularly coal, are also shown to increase.

Tables A-2 and A-3 give projected fossil fuel and nuclear power requirements. The number and size of plants recently constructed are shown in Table A-5 from Ref. A-3. The increasing electrical demands will require plant construction as shown in Table A-6 (Ref. A-5). The U.S. is expected to continue to build fossil-fueled generating plants over the next two decades at a rate consistent with those experienced in the 1965-1970 era. Nuclear-fueled plant construction is expected to increase rapidly and approach 35 new 1000 MWe nuclear units per year between 1980-1990. The attendant requirements for nuclear plant sites and demands for high-voltage transmission lines and routing are also illustrated in Table A-6.

Also, over the next two decades the Federal Power Commission projects the need for 300 electric power plant sites and the construction thereon of 300 generating stations with an average capacity of 3,000 MWe each. Additionally, some 7 million acres of new land will be needed for electric energy transmission.

The trend is toward large plants to capitalize on the economy of scale. However, in no circumstance will the single station output exceed the 10-15% reserve of the total network base load. Hence, a preponderance of joint ventures

Table A-5. Number and size of electrical plants (Ref. A-3)

Size of Units (MW)	Number of Units Constructed		
	1970	1971	1972
500 and over	19	32	35
200 - 499	14	13	16
100 - 199	9	9	4
4 - 99	16	14	10
Total	58	68	65

Table A-6. New plant forecasts (Ref. A-5)

	Actual	Estimated	
	1965-1970	1970-1980	1980-1990
Number of 1,000 MWe Units needed per year			
Fossil-fueled	15	15	16
Nuclear-fueled	2	14	35
Number of nuclear sites needed per year	2	7	17
Thousands of miles of transmission lines needed per year			
< 200 KV		5	5
> 200 KV		5	5

appear in the offing where several utility companies will share in the operation of central stations.

For the purpose of the LMMHD study, plant size was assumed to be 1000 MW electrical output and the number of plants required is given in Table A-6.

F. ELECTRICAL POWER GENERATION AND THE ENVIRONMENT

There has recently developed in the country a greater awareness of the need to preserve the environment. As a result, restrictions are being placed upon electrical power generation and distribution. If the LMMHD system is to be applicable to future power generation, it must be capable of meeting projected environmental standards and restrictions. Specific environmental characteristics restricting the electrical power industry are

1) Air quality.
2) Water quality.
3) Radiation levels.
4) Land use.
5) Aesthetics (noise, appearance, etc.).

The effects the alternative systems have on the environment, compared with LMMHD, have been summarized in Appendix B, Section F. Also, an evaluation of the effects on the environment of an LMMHD/steam binary plant is made in Appendix F, Section E. Siting considerations are also discussed in the following section of this Appendix.

The Clean Air Quality Act Amendments of 1970 have placed restrictions on fossil fuel-fired power generation with the following results: particulate removal systems have been developed and implemented; the use of low sulfur fuels have been emphasized; sulfur removal techniques are being developed; modified combustion techniques and flue gas recirculation are used to reduce nitrogen oxide formations; and nuclear power is being introduced to base loading at a rapid rate.

The primary effects of electrical power generation on water quality are: heat addition, discharge of chemicals, and release of trace amounts of radioactivity. Of these effects thermal pollution is the most significant. The "once through" cooling typically used produces about 1500 cfs flows for 1000 megawatt fossil-fueled plants. The discharge is typically 10° to 30° warmer than the inlet, mixes with the receiving body, and, depending upon local conditions, often quickly reaches ambient temperature a few hundred yards from the discharge.

Studies of the effect of warm-water discharge have also shown little adverse effect on water quality when the discharge is properly controlled (Ref. A-4). Nevertheless, the Water Quality Act of 1965 and the subsequent Water Quality Criteria issued by the Federal Water Quality Administration have established water quality requirements for power plants. The result is that future plants will tend to have closed cycle water cooling systems, such as cooling towers or ponds, with the attendant increase in cost, land use and esthetic problems of plant design.

Radioactivity released from nuclear power plants is regulated by the U.S. Atomic Energy Commission, which also licenses the facilities. Standards for radiation levels are now established by the Environmental Protection Agency. These are set at 1% of the exposure established by the Federal radiation guidelines for the general public. Experience with nuclear power facilities has shown little difficulty in compliance with the regulations. On the contrary, nuclear-power-plant radiation has usually been lower than the allowed value.

The power industry uses large amounts of land, creating plant siting problems. There has been a trend toward location of plants a considerable distance from load centers, reducing land use conflicts but presenting problems regarding land use rights-of-way for transmission, and the use of "unspoiled country" which some contest should be preserved. This subject is treated in more detail in the following section.

The industry has made significant advances in improving the appearance of plants and transmission lines, but much remains to be done. Particular emphasis should be placed on replacing overhead transmission lines with underground installations, including the high-voltage transmission lines.

G. SITE CONSTRAINTS AND CONSIDERATIONS

Site constraints can influence future plant selection as well as location. It is necessary to understand what impact this could have on LMMHD implementation. Therefore, the following background information is presented.

Systematic identification and commitment of power plant sites is based upon a weighted ranking procedure that considers the effect of different parameters in arriving at an overall ranking of various alternate sites. Site constraints include the assessment of economic, geological, meteorological, and environmental considerations which are all interrelated. For example, the assessment of air pollution will involve an evaluation of site meteorology and dispersion potential, and site remoteness.

Additionally, thermal pollution and waste disposal assessment will include an evaluation based upon effects of thermal and waste discharges upon the water supply as well as the disturbances inflicted upon the aquatic community. Compatibility assessment of the site with the general area development plan will also include the consideration of aesthetic factors and noise and population proximity to nuclear plants. Community considerations include enhancement or withdrawal of areas for recreation and the consideration of economic benefits to the area arising from the installation of the unit.

In a recent study conducted by the Committee on Power Plant Siting for the National Academy of Engineering, an analysis of electric energy needs and power plant siting was conducted and resulted in the following conclusions (Ref. A-6):

1) Utilities are currently faced with a chaotic situation with respect to the availability of suitable and adequate fossil fuel supplies for present and future generating stations. This situation greatly compounds the difficulties of planning and siting new facilities.

2) Since nuclear power plants discharge a minimum amount of air pollutants, do not require nearby fuel sources or major fuel handling facilities, can be made aesthetically attractive, and remove a minimum amount of land from public use, this mode of generation will provide an ever-increasing percentage of future electrical capacity, providing there is an adequate source of nuclear fuel.

3) Although not free from environmental impact, hydroelectric power provides a means of generating electricity that causes little contaminants to be discharged into either the air or water environs. (Nitrogen ingestion into the water due to the turbulence created has been determined to kill fish. Control mechanisms are now being investigated). Because of the limited availability of hydroelectric sites in most parts of the United States and the large amount of land required for reservoirs, however, this method of generation will not provide a major portion of future electrical requirements.

4) Pumped storage hydroelectric plants provide an effective means for utilities to maximize use of existing generating facilities to meet peak load demands. Due to the large amount of land required for reservoirs and the inability of these systems to operate without receiving energy from other generation facilities, pumped storage plants will provide only a small portion of future electrical capacity.

5) Technology exists for extra high voltage transmission for both alternating and direct current, which allows for great flexibility in generating plant location, including remote siting. The principal noneconomic constraint in the development of such transmission is public reaction to the presence and appearance of these facilities.

6) There is high probability of achieving solutions to the sulfur dioxide problem within the next decade by fuel desulfurization and flue gas scrubbing systems. Development of two-stage combustion has demonstrated that the production of nitrogen oxides may be reduced to approximately 50 to 25 percent of previous levels in many large fossil boilers, depending upon the boiler design or fuel being used. New techniques that will allow significant reductions of nitrogen

oxide emissions have not yet been developed. Hence, the siting of new fossil plants or expanding existing plants in a number of large cities will be precluded.

7) All steam generating facilities reject heat into the atmosphere. Condenser cooling water discharged into another body of water transfers heat to the atmosphere by evaporation, radiation, convection, and conduction. When cooling towers are employed, heat is rejected directly to the atmosphere primarily by evaporation in wet cooling towers or by convection in dry cooling towers. Each type of system has its environmental advantages and disadvantages which must be thoroughly investigated before deciding which method of cooling should be employed at a particular generating site.

8) Electrical generating facilities and their associated transmission and distribution systems require significant amounts of land. When constructing such facilities, efforts must be made to make them as compatible as possible with surrounding structures and land areas.

9) As a result of the increased concern for the environment by local, state, and federal governments, a great amount of new legislation is being considered. It is important that any such legislation reduce to the maximum extent possible the difficult task of securing permits, licenses, and approval from the many agencies, boards, and districts at all government levels, and approach as closely as feasible a one-stop review process to consider the public interest as a whole.

Inasmuch as the site considerations are general in nature, it is imperative that the utilities select sites with the greatest adaptability to a number of alternative power generation modes in order to maximize the probability of future site development.

H. FINANCING ELECTRICAL INDUSTRY GROWTH

Financing new concepts is one of the most serious obstacles to their development and commercialization. The following paragraphs give background information on the present and future financial outlook.

The capital outlays required by the electrical industry in the 1970-1990 period have been estimated (Ref. A-4) to be of the order of $400 to $500 billion, at 1970 prices. Based on the present pattern of financing it is estimated that 40% will be provided by internal sources, mainly through depreciation accruals and retained earnings; and 60% will be obtained competitively in the capital market. The primary source of external funding will be through the sale of bonds.

The past record of successful financing and reasonable returns on investment indicates that there have been no great difficulties in providing adequate financing. Timing of the financing with construction will require continued close consideration to avoid delayed construction and thus potential supply problems. Thus far there have been no such significant financing problems. "The further ability of the industry to finance its growing requirements for new capital on schedule and on acceptable terms will depend largely on how well it will be able to compete with other borrowers of capital" (Ref. A-4).

Research and development (R and D) goals have been set forth in Ref. A-7. Methods of financing the R&D required to achieve the established goals is currently being studied. Some observations can be made now, however.

1) There will be a need to increase present funding for R&D to accomplish the established goals.
2) Because the manufacturing industry is so diverse, it may not provide substantial increases.
3) Government funding is growing and will probably continue to grow for some time.
4) The utilities can be expected to increase participation through some form of increased combined commitment. The formation of the Electric Power Research Institute is an example of this trend.

I. RESEARCH AND DEVELOPMENT NEEDS AND TRENDS

Research and development (R&D) goals for the period through 2000 were established by the Electric Research Council in Ref. A-7. Many factors were considered in setting the goals including needs, costs, priorities for a balanced program, etc. However, these R&D goals were established without a detailed examination of LMMHD applications. The following presents the current outlook for R&D goals as given in Ref. A-7 with comments regarding the priority of LMMHD based upon the analysis herein.

Since energy conversion is the primary consideration of this study, the specific goals of Ref. A-7 for energy conversion are given as follows:

"1) Establish nuclear breeder reactors as being commercially available for purchase by the mid 1980's for central station baseload applications.

2) Improve present methods of generation in efficiency, reliability, and environmental impact. Continue development of gas turbine-steam combined cycle.

3) Establish scientific feasibility of nuclear fusion within 5 to 8 years and make it commercially available for purchase by the mid 1990's for central station base-load applications.

4) Establish gasified coal fuel as economically available for gas turbines, MHD and conventional boilers by 1975. Continue research on other methods of fuel preparation such as hydrogen production and solvent processing.

5) Establish open cycle MHD as being commercially available for purchase by the mid 1980's, using gas, oil, coal, or coal derived fuel, for central station base-load applications topping either steam or gas turbines. Establish the MHD portion of these combined cycle plants for peaking and emergency power requirements.

6) Establish fuel cells in the 10-20 MW size range as being commercially available for purchase by the late 1970's for substation application, fueled by natural gas, hydrogen, or fuels derived from coal or oil.

7) Continue research on high energy bulk storage batteries for peaking purposes.

8) Continue R&D for unconventional cycles such as potassium-steam binary cycle and Feher CO_2 cycle. Continue research on thermionics for topping nuclear and fossil generating plants.

9) Proceed with additional research on solar energy at a moderate funding level.

10) Continue basic research for new methods of energy conversion."

Table A-7 shows the priorities and annual costs for each of the recommended energy conversion programs. Note that whereas LMMHD is not mentioned in the specific goals, it is listed in Table A-7 as a fourth priority item. Also, LMMHD is mentioned as a prime candidate as a topping cycle for the nuclear fusion system, goal 3 above. Based upon the results of the analysis herein, which indicates a favorable comparison of LMMHD with other systems, it would seem that LMMHD should receive a higher priority. The priorities are as follows:

"Priority 1 - Critically important: projects having an indispensable effect on all of our goals, which by their nature must receive first attention.

Priority 2 - Very important: projects having a somewhat less intense impact; but which nevertheless must be included in any meaningful R&D program.

Priority 3 - Important: projects of significance to future planning and continuing operations.

Priority 4 - Desirable: other projects which are useful to accomplish stated goals."

Note that only projects in priority 1 have been allocated sufficient funds to assure development for commercial applications. Funds allocated for other projects should allow demonstration of the concepts, but will not be sufficient to provide a marketable product without additional funding.

In setting specific R&D goals, the task force was guided by the following principles:

"1) Aggressively pursue a balanced R&D program that will keep energy conversion options open. Opportunities for short term benefits to the industry and the public cannot be passed by in

Table A-7. Energy conversion R&D summary of costs to utilities, manufacturers and government (Ref. A-7)

Priority	Project	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981 1985	1986 1990	1991 2000	TOTALS
		(Millions of 1971 Dollars)												
1	Breeders	250	340	369	427	432	476	415	331	208	500	250	200	4,198
	Fusion	50	60	95	110	135	160	170	215	245	1,000	1,000	1,000	4,240
	Present Methods	165	180	195	210	225	240	255	270	285	1,650	2,025	5,175	10,875
	Fuel Processing	8	10	10	15	10	6	2	2	2	5	5		75
	Subtotal	**473**	**590**	**669**	**762**	**802**	**882**	**842**	**818**	**740**	**3,155**	**3,280**	**6,375**	**19,388**
2	MHD – Open Cycle	4.2	4.4	4.7	9.5	16.2	14.4	5.0	4.5	30.0	120.0	25.0	–	237.9
	Fuel Cells	6.5	8.0	4.0	4.0	3.0	2.0	2.0	2.0	2.0	5.0	–	–	38.5
	Bulk Energy Storage	5.0	5.0	6.0	6.0	4.0	4.0	5.0	5.0	5.0	5.0	10.0	–	60.0
	Subtotal	**15.7**	**17.4**	**14.7**	**19.5**	**23.2**	**20.4**	**12.0**	**11.5**	**37.0**	**130.0**	**35.0**	**–**	**336.4**
3	Unconventional Cycles	6.0	6.0	9.0	9.0	6.0	4.5	3.0	3.0	3.0	7.5	–	–	57.0
4	Solar Energy Conversion	3.0	3.0	4.0	4.0	4.0	8.0	10.0	15.0	17.0	45.0	30.0	25.0	168.0
	MHD-Liquid Metal	0.3	0.8	0.8	1.0	1.0	2.0	2.0	5.0	5.0	10.0	5.0	–	32.9
	MHD-Closed Cycle	1.0	1.0	1.0	1.5	1.5	2.0	2.0	2.5	2.5	25.0	45.0	30.0	115.0
	Thermionics	1.0	1.0	2.0	2.0	3.0	3.0	2.0	2.0	1.0	2.5	2.5	–	22.0
	Subtotal	**5.3**	**5.8**	**7.8**	**8.5**	**9.5**	**15.0**	**16.0**	**24.5**	**25.5**	**82.5**	**82.5**	**55.0**	**337.9**
	TOTALS	**500**	**619**	**701**	**799**	**841**	**922**	**873**	**857**	**806**	**3,375**	**3,398**	**6,430**	**20,119**
	Unassigned	—	—	—	—	—	—	—	—	—	**500**	**700**	**2,000**	**3,200**
	Totals Including Unassigned	**500**	**619**	**701**	**799**	**841**	**922**	**873**	**857**	**806**	**3,875**	**4,098**	**8,430**	**23,319**

anticipation of larger benefits in the longer run, no matter how much greater the potential long-run benefits; nor can long term R&D be sacrificed for short term gains. And in both the short and long term there is need for alternatives. In neither the short term nor the long term do we know of any single concept so promising in every area of importance to the industry and the public that it would justify scaling down alternative efforts.

2) Assure that there will be several competitive means of generating electricity to provide choices to fit differing requirements, to stimulate innovations by manufacturers, and to avoid excessive dependence on one or two systems, or on designs which have limited opportunity for substantial further improvement.

3) Direct research toward methods which do not place excessive demand on our precious high grade natural fuel resources. Such demand would cause not only instability of price and insecurity of supply, but could also waste irreplaceable commodities having great value for uses other than fuel.

4) Make fossil fuels adaptable to more exotic power generation devices.

5) Improve power plant efficiency to conserve fuel, minimize waste heat and keep power costs reasonable.

6) Improve reliability to minimize requirements for backup capacity and to assure continuity of service.

7) Provide for the most economical mix of power generation methods, with consideration for peaking, intermediate and base load operations, decentralized small generation and energy storage facilities.

8) Design future energy conversion systems with the aim of minimizing transmission requirements to the extent possible.

9) Make most efficient use of plant sites by planning to install maximum feasible capacity on each site.

10) Maintain flexibility to adjust priorities to fit changing conditions and take advantage of emerging commercial technologies."

The Electric Research Council has a task force studying the R&D financing problem. It has been recommended that the electric utility industry contribution be increased to as much as $150 to $200 million per year, while continuing the present levels of funding by federal, state and local governments.

One of the more promising methods of raising the money in the private sector is to have coordinate industry-wide commitments. Participating utilities would contribute an amount based on their level of sales. This cost could then be passed on to the consumer. The participating agency would then be assured access to the results of the R&D.

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APPENDIX B

CHARACTERISTICS OF ALTERNATIVE SYSTEMS

A. INTRODUCTION

To establish the merit of LMMHD for applications to power generation, it must be compared with alternate methods of producing power. The characteristics of alternative power generation systems are presented in this Appendix. The analyses were based primarily on available references and consultation with experts in the field.

Power generation can be divided into several categories. System types selected for comparison with LMMHD include: fossil-fuel steam plants, open cycle plasma MHD/fossil fuel steam binary plants, potassium Rankine/fossil-fuel steam binary plants, gas turbine/fossil-fuel steam binary plants, light water nuclear reactor plants, gas-cooled thermal nuclear reactor plants and liquid metal fast breeder nuclear reactor plants. A rationale for the elimination of other power conversion methods is presented and a brief description of the selected systems is provided.

For each of the selected systems the following characteristics have been defined for the specified 1000 MW* base load plants:

1) Efficiency and load factor.
2) Economic factors:

    a) capital costs.
    b) fuel costs.
    c) operations and maintenance costs.

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* 1) See Appendix A, paragraph E, for plant size discussions and the rationale for selection of this value.

2) For convenience the LMMHD/steam system was designed (Appendix E) for a 2500 MW heat input to the LMMHD cycle. This resulted in a total power output of 1637 MW. Costs and environmental factors were then normalized to 1000 MW for comparison with the alternative systems.

3) Environmental factors:

   a) Air pollution.
   b) Thermal pollution.
   c) Radioactive pollution.

4) Other characteristics:

   a) Lead time.
   b) Availability date (if currently not developed).
   c) Technology growth potential.

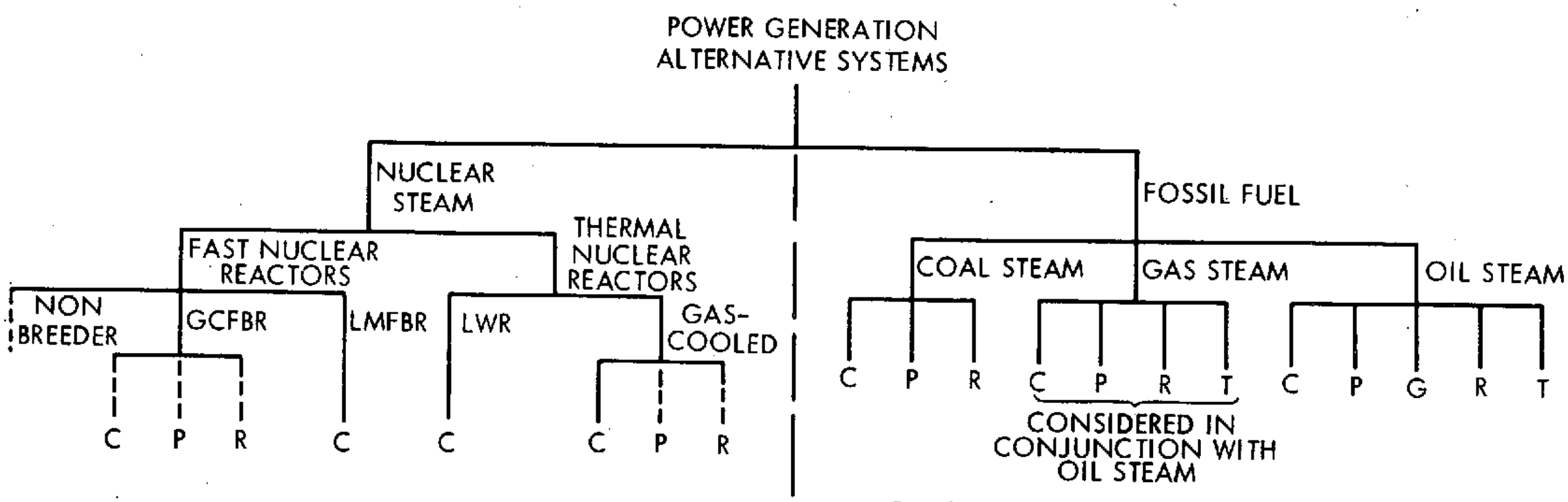
It was beyond the scope of this study to consider reliability, maintainability, and safety.

B. ALTERNATIVE SYSTEM SELECTION RATIONALE

Figure B-1 shows the possible alternative systems which could have been considered in this study. The solid lines indicate those systems which were considered; the dotted lines indicate the systems not considered. The power generation systems compared with LMMHD/steam binary plants were the following:

1) Coal-fired steam plants.
2) Oil/gas-fired steam plants.
3) Open cycle plasma MHD/fossil fuel steam binary plant.
4) Gas turbine/fossil fuel steam binary plant.
5) Potassium Rankine/fossil fuel steam binary plant.
6) Light water nuclear reactor (LWR) plants.
7) Gas-cooled thermal nuclear reactor (GCR) plants.
8) Liquid metal fast breeder nuclear reactor (LMFBR) plants.

The remaining possible systems have not been considered for the reasons given in the following paragraphs.



C - CONVENTIONAL BASE LOADING

P - OPEN CYCLE PLASMA MHD TOPPING/STEAM BINARY

R - POTASSIUM RANKINE TOPPING/STEAM BINARY

T - GAS TURBINE BASE LOADING

G - GAS TURBINE/STEAM BINARY

OTHER METHODS NOT CONSIDERED
- HYDROELECTRIC
- GEOTHERMAL
- SOLAR ENERGY
- THERMIONIC
- FUSION
- CHEMICAL BATTERIES
- FUEL CELLS
- CLOSED CYCLE PLASMA MHD
- CLOSED CYCLE GAS TURBINE
- ALL TERNARY PLANTS

——— SYSTEMS CONSIDERED

- - - SYSTEMS NOT CONSIDERED

Fig. B-1. Power gneration alternatives

There are advanced power conversion systems, which are in a similar state of development as LMMHD.

1) Closed cycle plasma MHD topping cycle — Closed cycle plasma MHD permits non-equilibrium ionization to be established (using cesium-seeded argon), allowing much greater gas conductivity and MHD action at lower temperatures (1500° F to 3000° F) than for the open cycle plasma MHD. However, work is still in the very early stages and scaling up early results has yet to be successfully demonstrated. For this reason and because of the limited scope of the study, closed cycle plasma MHD is not considered further in this study.
2) Thermionic topping cycle — Thermionic conversion is being developed for space applications, but as yet its use as a major utility power source has not been economically demonstrated. The scale-up for the large-scale power generation is considered feasible, but funding to carry out the required research and development is currently lacking. It operates at higher temperatures than LMMHD and may be applicable to a ternary plant (Refs. B-8 and B-17).

Other advanced power generation systems which were not considered in the comparison, since their probable commercial development is beyond the period (to 1990) considered in this study, include the following:

1) Nuclear fusion plants - The feasibility of controlled nuclear fusion has not been demonstrated. The advanced experiments have not yet demonstrated the simultaneous achievement of the required plasma density, plasma temperature, and confinement time necessary for a practical fusion reactor (Ref. B-17). Although not addressed in detail in this report, the application of LMMHD as a topping cycle to a nuclear fusion plant is a promising application (Ref. B-14). The fusion system would have high enough source temperatures, and lithium, required by the LMMHD System, is used as a coolant.

2) Fuel cell plants - Although demonstrated as small units, fuel cells are considered to be uneconomical for large power generation systems (Refs. B-1, B-5, and B-17).

3) Solar energy plants - Solar powered systems developed thus far have been small-scale and not applicable to efficient and economic large-scale electric power generation. Ground based systems require large areas, high capital costs and the need for a low percentage of cloudy days. Space-borne systems, which beam to earth power produced by solar cells, probably will not be developed during the period considered in this study (Ref. B-5).

4) Gas-cooled fast breeder reactors and molten salt fast breeder reactors - These systems are currently receiving secondary emphasis by the AEC compared with the liquid metal fast breeder reactor (LMRBR), and although they are considered competitive with the LMFBR, their development will probably lag behind the LMFBR and be beyond the period considered here (Ref. B-5).

5) Closed-cycle gas turbine - There is no indication that there is sufficient interest in this system to indicate that it will be developed for commercial application during the period considered in this study.

6) All ternary plants - Many feasible ternary plants can be postulated, including ones using LMMHD; however, their development would be beyond the period considered.

Systems not to be considered in the comparison because of their geographical limitations are

1) Hydroelectric facilities.
2) Geothermal facilities.

Other systems not being considered in the comparison are the following:

1) Gas turbine base loading - Due to its relatively low efficiency and small unit size, this system is presently being used primarily for peaking plant operation which is not an application being considered for LMMHD. It is anticipated that gas turbine efficiencies will be

improved to allow it wider application; however, the gas turbine/ fossil fuel steam binary plant is considered a stronger competitor for base loading plants and thus has been selected for comparison in this study.

2) Miscellaneous topping cycles/nuclear steam binary plants - Nuclear reactor systems currently being designed and constructed have source temperatures too low for application of topping plants. If advancements in nuclear reactor technology should provide higher source temperatures, LMMHD could advantageously be applied to reduce specific capital costs ($/kW) and increase plant efficiency. This application and the application to nuclear fusion plants could be as significant in the long run as the application of LMMHD as a topping cycle to fossil fuel plants which is the primary consideration of this report.

C. ALTERNATIVE SYSTEM DESCRIPTIONS

Brief descriptions of the alternative systems, selected in the foregoing section for consideration in this study are as follows.

1. Fossil Fuel Steam Plants

Fossil-fuel plants utilizing the Rankine steam cycle have been the primary electrical power producers in the past. Fossil-fuel steam plants may be divided into three main categories by the fuel utilized: coal, gas, and oil. Although the percentage of electrical production by fossil-fueled plants is predicted to decrease from the present 80% to 35% in the year 2000 (see Appendix A), the actual energy produced by this type of plant will be nearly doubled. With this increase in fossil fuel usage, the nation's reserves, particularly of gas and oil, are swiftly diminishing. Increased reliance on foreign oil is predicted and coal usage may increase. No major changes, which might affect plant efficiency or capital cost, are expected in fossil-fuel plant design during the period under consideration in this study (through 1990), except in areas of pollution control (Ref. B-17).

2. Open Cycle Plasma MHD/Fossil-Fuel Steam Binary Plants

Plasma magnetohydrodynamics (MHD) is a direct conversion method for obtaining electrical energy, utilizing a heat source to produce a high velocity, electrically conductive, gas stream which interacts with a magnetic field to produce electrical power. Fossil-fuel combustion products, seeded with cesium or potassium are generally considered for the working fluid. Open cycle operation is the most likely near-term plasma MHD cycle to be developed (Ref. B-1). Plasma MHD requires heat source temperatures on the order of 4500°F with output temperatures typically 3500°F. Therefore, plasma MHD is generally considered to be a topping unit for use with a steam bottoming plant. Because of the need for extremely high temperatures for successful plasma MHD operation, most proposals consider coupling with fossil power plants rather than nuclear plants. Nuclear plants with heat source temperatures high enough for applications of plasma MHD as a topping cycle are far in the future.

Plasma MHD/fossil fuel binary plants are predicted to be capable of thermal efficiencies of 50% or higher. The major technological problems are: achieving high levels of enthalpy extraction, long life insulating walls, durable electrodes for plasma MHD generators, and pollution control. These problems are currently being investigated in demonstration units now being operated. Other problems listed in Ref. B-1 include coal combustion problems, requirements to improve generator efficiency and requirements to improve the prediction of gas electrical conductivity (in order that the power output can be predicted with accuracy).

3. Gas Turbine/Fossil-Fuel Steam Binary Plant

Whereas gas turbines for stationary power plants are presently restricted primarily to peaking plant operation, combined gas turbine/fossil-fuel steam plants are being offered for mid-range power applications (Westinghouse Electric Corp., General Electric Company, Turbo Power and Marine Systems, Inc., Turbodyne Corp., and Stone and Webster Engineering Corp. (Ref. B-2)). Because of projected efficiency gains, the gas/turbine steam binary plant offers the potential for extensive base plant operation. These efficiency increases are predicted on the basis that gas turbine technology has not yet reached maturity, as has fossil-fuel steam technology, and, therefore, significant improvements are possible. In particular, efficiency improvements are projected to be achieved by increasing the compressor pressure ratio and turbine inlet temperature. The latter is predicted to be achieved by the use of new and improved materials and blade cooling (see Refs. B-1 and B-3 for a summary of the predicted technology achievements).

There are several possible design variations for the gas turbine/steam binary plant, but the variation which simply utilizes the gas turbine's waste heat to produce steam is projected to be the most promising for future designs (Ref. B-1).

4. Potassium Rankine/Fossil-Fuel Steam Binary Plant

Liquid metal topping cycles using mercury have been operated in the past. But as the steam cycle became more efficient (steam temperature increased) mercury topping cycles became less desirable due to temperature limitations of the working fluid. Potassium employed in a Rankine cycle overcomes the temperature limitations of mercury and provides a viable option for future topping cycles. It would be preferred over cesium due to its lower cost. The potassium Rankine topping cycle can be either retrofitted to existing steam power plants or it can be built as a new installation. In either case, it can achieve efficiencies which can be considered competitive with or greater than the other binary plants considered in this study.

There has been considerable experience with components utilizing potassium over the past ten years, particularly work conducted at the General Electric Company and research at the Oak Ridge National Laboratory (Ref. B-4). If a low temperature (1500° F) system were selected, there would be no significant materials problems anticipated in the development of the potassium turbine piping system. Efficiencies for the system at these temperatures are predicted to be about 45%. Stainless steel materials would be acceptable. Turbine blade erosion, and the development of adequate seals are obstacles to overcome in the development of this system. However, to achieve high efficiencies, new, advanced materials would be required. The solution of these problems and the development of these materials is a key element to the successful technological growth of this system.

5. Light Water Nuclear Reactor (LWR) Plants

Nuclear power is just beginning to be a prominant factor in electrical power generation. Light water reactors have been the most prevalent systems utilized thus far. Light water reactors, which use water as a coolant and a moderator, are of two basic types: pressurized water reactors (PWR) and boiling water reactors (BWR).

In pressurized water reactors (PWR), water is both the coolant and the moderator. Water (under extreme pressure so that steam cannot form) is used in the primary circuit, where it absorbs heat generated by fission in the fuel rods. The heated water is pumped from the reactor core to a heat exchanger, where a secondary circuit (containing water also) absorbs the heat to become steam, which in turn is used to drive a turbogenerator. Boiling water reactors (BWR) use the same principles as a PWR except that in the BWR, the water is allowed to boil.

6. Gas-Cooled Thermal Nuclear Reactor Plants

Another type of thermal reactor is a gas-cooled reactor. The advanced helium cooled reactors will have temperatures and pressures equivalent to those in fossil-fueled generators--about 25% more efficient than water cooled nuclear reactor plants. Reduced heat discharge in the new system makes the reactor more suitable for water-short areas than water-cooled units. Although gas-cooled thermal reactors have seen only limited use in the past, (Philadelphia, PA and Rt. St. Vrain, Colo.) they are being considered for implementation in the California desert and in the Philadelphia, PA area. They may, therefore, be employed increasingly in the future.

7. Liquid Metal Fast Breeder Nuclear Reactor (LMFBR) Plants

A reactor design important in the development of advanced reactors is the sodium-cooled fast reactor. Its principle lies in the sodium's ability to absorb the highest possible core temperature while remaining liquid over a wide temperature range and not act as a moderator. Sodium is used in the primary coolant, but the system requires a secondary (or intermediate) coolant loop. This is because sodium becomes highly radioactive in the reactor core, which would contaminate the water in the steam circuit.

The breeder reactor converts useless isotopes of uranium or thorium into rich fuels of U-233 or plutonium. The doubling time (the time to double the amount of fuel present initially) is typically from eight to fifteen years. Breeders could increase supplies of fissionable materials a hundred times over, while supplying energy at costs equivalent to that of conventional reactor types. FBR's, with their short doubling times could create enough fuel to last a thousand years. The greater fuel efficiencies counteract increased capital costs to produce total power costs equivalent to current nuclear reactors. If fuel cost escalation is considered, the LFMBR could show significant future cost advantages. The LMFBR is receiving considerable attention and is predicted to be available beginning in the period 1982-1986, which is toward the end of the period considered in this study.

Problem areas to be resolved in the development of the liquid metal fast breeder reactor (Ref. B-1) are: development of an adequate fuel element; provision for core stability control (a safety issue); transportation, processing, etc. of the fuel elements which are more radioactive than those used now; prevention of sodium leaks (a safety issue); and protection of fuel theft (a national security issue). Note that there are several safety questions to be resolved in the development of this concept. Construction of demonstration units are planned to resolve these and other problems (Ref. B-14). Demonstration plants would be constructed beginning in 1972 with commercial availability by 1986.

D. ALTERNATIVE SYSTEMS' PERFORMANCE - EFFICIENCIES AND CAPACITY FACTORS

Efficiencies and capacity factors for the selected alternative systems are presented in Table B-1. The sources for the data are also shown in the table. The basis for the data presented are discussed as follows.

Table B-1. Alternative system performance - efficiencies and load factors

Operating System (1000 MW)	Plant Efficiency (%)			Load Factor		
	Late '70s	1980s	Values Used in the Analysis	Avg. Hrs. on Line/Yr(4)	Capacity Factor (%)	Full Load Capacity Factor (%)
1. Fossil Fuel Steam Plant (Coal)	40	42	40	6, 600	75(4)	75
2. Fossil Fuel Steam Plant (Oil/Gas)	40	42	40	7, 600	63(4)	80
3. Open Cycle Plasma MHD/ Fossil Fuel Steam Binary Plant	--	50-60(1, 2)	50	--	60(5)	70
4. Gas Turbine/Fossil Fuel Steam Binary Plant	45(1, 2, 3)	52(2, 3)	48	5, 900	60(4)	75
5. Potassium Rankine/Fossil Fuel Steam Binary Plant	45(3)	51(3)	48	--	60(5)	75 (Coal-fired) 775 (Oil-fired)
6. Light Water Nuclear Reactor Plant	32(2)	33(2)	33	7, 100	80(4)	80
7. Gas-Cooled Thermal Nuclear Plant	39(2)	39(2)	39	--	80(6)	80
8. Liquid Metal Fast Breeder Reactor Plant	--	40(2)	40	--	80(6)	80

NOTES:

1. Ref. B-5.
2. Ref. B-1.
3. Ref. B-3.
4. Data from private communications.
5. Assumed to be the same as the gas turbine/steam binary plant.
6. Assumed to be the same as the light water nuclear reactor plant.

1. Efficiencies

Efficiency predictions are shown in Table B-1 for the late 1970's and 1980's. Also shown are the efficiency values used in the study. The efficiencies given for fossil-fuel steam plants, light water nuclear reactor plants and gas-cooled thermal nuclear reactor plants are reasonably accurate, based on the references.

Efficiencies for advanced plants are not as easily predicted due to developmental uncertainties for these systems. The efficiencies used in the study have been selected to represent reasonable and comparable values for the mid-1980 period and do not necessarily represent the maximum values achievable. The efficiency for the combined cycle gas turbine/steam binary plant have been presented in several sources and is based on technology advancements from the present. The prediction given is from Refs. B-1 and B-3. It is based on reasonable advances from present technology (a turbine inlet temperature of 2400° F), but does not represent the maximum achievable. References B-1 and B-5 were the sources for efficiencies estimated for the open cycle plasma MHD/steam binary plant. The lower end of the predicted efficiency range was selected for use in this study due to the difficult technology problems which must be overcome to develop the plasma MHD concept. (Lower values were also selected for LMMHD for similar reasons.) References B-3 and B-4 were the source for the potassium Rankine/steam binary plant data. The efficiency for the late 1970's corresponds to a low temperature system using available materials; the 1980 value is a maximum value for a high temperature system using advanced materials. The selected efficiency for use in this study is an average of the two and is representative of liquid metal temperatures assumed for the LMMHD system and achievable by the potassium Rankine/steam system. Reference B-5 was the source for the liquid metal fast breeder reactor plant efficiencies.

It was assumed that the open cycle plasma MHD/steam binary plant and the liquid metal fast breeder reactor plant would not be developed for commercial operation before the 1980's. The potassium Rankine/steam binary plant may not be available for the 1980's, but the low temperature (1500° F) system could be developed by the late 1970's, given sufficient funding.

2. Capacity Factors

The capacity factors shown in Table B-1 are based on data from private communications with industry, and were assumed to be the same for the late 1970's and 1980's. They were generated on the basis that coal-fired fossil fuel and nuclear plants operate at 100% load when on line, and that oil/gas-fired fossil fuel plants and combined cycle gas turbine/steam plants are swing plants which do not operate at full load all of the time they are on line. Oil/gas and gas turbine combined cycle plants have the ability to follow sharp changes in load faster than other unit types and thus are suited to swing plant operation. In addition, fuel costs are such that these plants can only be justified when operated at a lower capacity factor.

Average hours on line/year and capacity factors were not available for the other four selected systems. The two advanced binary systems were assumed to have capacity factors the same as the combined cycle gas turbine/steam binary cycle. However, it is possible that the plasma MHD/steam system would have a lower capacity factor due to maintenance resulting from the high temperature corrosive environment. It has been estimated, for example, that the plasma MHD channel would have to be replaced monthly. The two nuclear plants for which data were unavailable were assumed to have capacity factors the same as the light water nuclear reactor plant.

Comparisons of LMMHD with the alternative systems were made assuming that all plants operate at full load. The full load capacity factors assumed for that comparison are shown in the last column of Table B-1. Note that the plasma MHD system is again considered lower than other systems due to the maintenance requirements. By using the influence coefficients given in the following section it is possible to compare systems under varying operational assumptions.

E. ALTERNATIVE SYSTEMS' COSTS

Costs have been developed for the alternative systems. Since the study is limited to comparison of generation systems, only generation costs are presented. Therefore, transmission costs, administration costs, etc. are not included. System generation costs for the selected alternative systems were developed for the categories: capital costs, fuel costs, and operations and maintenance costs. Since there is a wide variation in costs dependent upon region, design, and other factors, nominal costs have been selected for the Southern Pacific Coast-Southwestern United States region. Costs for all systems are based on projected 1980 costs. Some advanced systems will not be available by 1980. However, costs are available for these systems and have been normalized to 1980. In all cases the sources of the costs are listed and the reasoning behind modifications of the source data are given. The general cost study which follows includes an analysis based on nominal costs and other factors and presentation of influence coefficients which permit variation of these parameters. The analysis was based on nominal costs and influence coefficients rather than consideration of parametric variations due to the number of parameters to be considered and the difficulty in displaying the variation. Also, scenarios of possible future fuel restrictions were considered.

1. Capital and Fixed Costs

Nominal specific capital costs are shown in Table B-2 for the selected 1000 MW alternative systems. The capital costs for coal-fired steam, oil/gas-fired steam and light water reactor plants were available from several sources listed in the notes of Table B-2. The data from these various sources were adjusted to arrive at the nominal 1980 values shown. These are slightly lower than the projections of Ref. B-16.

Cost data for advanced power generation plants were not readily available. And since the scope of this study did not permit detailed evaluations of the costs that were available they are subject to greater error than the conventional power plant costs given.

Open cycle plasma MHD/fossil fuel steam costs were given in Reference B-19 as \$100 to \$120/kW for a first-generation plant. The specific capital cost used in the analysis was \$110/kW, 1968 costs. This cost was escalated at 5% per year, as practiced for all other systems. The binary system cost was determined using the same method used for the LMMHD/steam plant given in Appendix F, paragraph D-3. This gave a 1980 specific capital cost of \$300/kW. In Ref. B-5 plasma MHD costs were developed for each major component of the

Table B-2. Alternative system capital and fixed costs
(1000 MW plants; reference year 1980)

Parameter	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
Capital Cost, $/kW	320[1]	230[1]	300[5]	270[1, 3] (Dist. oil)	325 (Coal)[4] 260 (Oil)	400[1]	400[2]	500[2]
Financial Charges, %/Yr	15	15	15	15	15	15	15	15
Capacity Factor, %	75	80	70	75	75 (Coal) 77.5 (Oil)	80	80	80
Fixed Costs, Mill/kWh	7.3	4.9	7.4	6.3	7.4 (Coal) 5.7 (Oil)	8.6	8.6	10.7

NOTES:

1. Refs. B-6, B-7 and B-8 and data from private communications.
2. Ref. B-5 data scaled consistent with data from sources in Note 1.
3. Ref. B-2 data escalated at 5% year to 1980.
4. Ref. B-3 plasma MHD data used to calculate binary capital cost as in Appendix F, Paragraph D-3.
5. Ref. B-19 potassium Rankine system data used to calculate binary capital cost as in Appendix F, Paragraph D-3.

MHD system and then total plant costs were derived. However, considering capital costs currently projected for future power plants, the costs presented were low, and did not take into account recent rapid cost increases. Therefore, it was not possible to use the component costs given in Ref. B-5 to calculate plasma MHD/fossil fuel steam plant costs. The reference did show, however, that the projected plasma MHD/fossil fuel steam plant costs were 15% more than the conventional coal-fired steam plant. Thus, the capital costs used in the study, which are lower than conventional steam plants, are considered to be favorable to the plasma MHD system.

Gas turbine/steam binary plant costs were available from several sources listed in Table B-2. The capital costs shown in Table B-2 are those quoted by users, escalated at 5% to represent 1980 costs. It is also assumed that there is no increase in costs to account for the technological improvements (improved efficiency) used in this analysis. This is believed to be an optimistic assumption even though Ref. B-1 indicates a decrease in capital costs with increasing performance.

Costs given for potassium turbine plants in Ref. B-3 were used to establish specific capital costs. In that reference, the potassium Rankine system produced 320 MW of a 1000 MW binary power plant at a 1970 cost of $53 million. Escalating this cost at 5% per year to 1980, and applying the method of calculation used for the LMMHD/steam binary plant given in Appendix F, paragraph D-3, the specific capital costs were determined to be as shown in Table B-2.

The costs developed in Ref. B-3 were for a low temperature (and low performance) system. The low temperature system is costed here, even though the performance used is representative of a higher temperature system. Thus the costs are considered to be favorable to the potassium Rankine/steam system.

Gas-cooled nuclear reactor and liquid metal fast breeder nuclear reactor (LMFBR) costs were given in Ref. B-5. These costs are low based on the 1980 base year estimates in this study and were thus scaled with the light water reactor plant costs which were obtained from more up-to-date references, and which were estimated for 1980. In Ref. B-5, the gas-cooled thermal reactor plant costs were estimated to be slightly less (7%) than the light water reactor costs. For the purposes of this study, they were assumed to be the same as the LWR. The LMFBR was estimated to be about 25% more costly than the LWR. This percentage cost increase is reflected in Table B-2.

The fixed costs in mills/kWh are calculated as follows:

$$\text{Fixed costs (m/kWh)} = \frac{\dfrac{\text{Total plant cost}}{\text{Total plant output}}\left(\dfrac{\$}{\text{kW}}\right) \times \left(\dfrac{1000 \text{ mills}}{\$}\right) \times \dfrac{\text{Annual fixed chg}}{100}\left(\dfrac{\%}{\text{Yr}}\right)}{8760\left(\dfrac{\text{h}}{\text{yr}}\right) \times \dfrac{\text{Capacity Factor (\%)}}{100}}$$

The annual percentage carrying charge on capital costs is made up of factors shown as follows:

Component of Charge	% of Capital Cost/Year
Income	2.0
Depreciation	3.3
Federal Income Taxes	2.0
Bond Interest	4.0
Local Taxes and Insurance	4.0
Total Carrying Charge	15.3

A carrying charge of 15% is selected as the nominal value for this study. This factor is important in determining both absolute and relative generation costs. Power plants with high capital costs will be more affected by changes in the annual carrying charge than power plants with low capital costs.

Lead time variations were considered, but based on the discussion of Ref. B-15 were determined to have a minor effect on the cost comparison.

The capacity factors used in Table B-2 are the nominal full-load values from paragraph D.

Influence coefficients which can be useful in making cost trade-offs and determining effects of variation from the nominal values used in the analysis are shown in Table B-3. These are partial derivatives of the fixed cost with

Table B-3. Alternative system's fixed cost influence coefficients

Influence Coefficient	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
1. $\frac{\partial C_{fixed}}{\partial C_C} = \frac{10\ (F)^*}{(H)}$, $\frac{mills}{\$\ h}$ (Multiply by change in C_C, \$/kW, to get change in C_{fixed}, mills/kWh)	0.0228	0.0214	0.0245	0.0228	0.0228 (Coal) 0.0221 (Oil)	0.0214	0.0214	0.0214
2. $\frac{\partial C_{fixed}}{\partial (F)} = \frac{10\ C_{CAP}}{(H)}$, $\frac{mills\ yr}{kW\ h}$ (Multiply by change in (F), %/yr, to get change in C_{fixed}, mills/kWh)	0.4860	0.3280	0.4900	0.411	0.495 (Coal) 0.384 (Oil)	0.5700	0.5700	0.7130
3. $\frac{\partial C_{fixed}}{\partial (H)} = -\frac{10\ C_C\ (F)}{(H)^2}$, $\frac{mills\ yr}{kW(H)^2}$ (Multiply by change in (H), HR/yr, to get change in C_{fixed}, mills/kWh)	-1.11×10^{-3}	-0.70×10^{-3}	-1.20×10^{-3}	-0.94×10^{-3}	-1.13×10^{-3} (Coal) -0.87×10^{-3} (Oil)	-1.22×10^{-3}	-1.22×10^{-3}	-1.52×10^{-3}

C_{fixed} = Fixed Cost

(F) = Fixed Charge, %/yr

(H) = Average hours on line/year - h/yr.

C_C = Capital Cost, \$/kW

respect to the major parameters affecting the fixed costs. They can be used to determine the change in fixed cost from the nominal values by multiplying the appropriate coefficient by the change in the parameter of interest. Care should be exercised in using the capacity factor influence coefficient, $\frac{\partial \text{ Fixed Cost}}{\partial \text{ Capacity Factor}}$. Since fixed cost is non-linear with respect to capacity factor, the value of this influence coefficient should be used only for slight variations from the nominal. All other influence coefficients are valid for any value of the parameter.

2. Fuel Costs

Fuel costs are subject to increase and fluctuation even more than capital costs. There are many readily available published references on the causes of the change, including predictions of future costs. In examining the energy forecasts and in formulating long-range plans, consideration of regional fuel constraints must be assessed. Although increasing stringency on air pollution regulations will have a significant impact upon the competitive posture of candidate fuels, the general conclusions reached by the Federal Power Commission regarding the competitive stature of fossil and nuclear fuels by regions can be summarized in the following paragraphs (Ref. B-10):

a. New England and Middle Atlantic

With the exception of Central and Western Pennsylvania where low-cost coal is abundantly available, the New England and Middle Atlantic states do not have access to low-priced coal. The competitive fuels in these areas are the imported low-sulfur-residual oils in locations with deep-water port facilities, and nuclear fuels.

b. East North Central States

In these states coal has a marginal advantage over nuclear fuel. Most of the coal in this area, however, has a very high sulfur content and is not a competitor where air pollution regulations restrict the emissions of sulfur oxides. In an attempt to circumvent this problem area, Chicago has initiated the import of low-sulfur coal from Colorado.

c. West North Central States

Both coal and natural gas compete effectively throughout most of this area, in part because of the relatively small average size of units which are required to accommodate the incremental energy demand in the region. Gas is expected to remain the dominant fuel in Kansas and very low-cost, low-sulfur lignite will predominate in North Dakota. In Missouri, high-sulfur coal has a significant advantage over nuclear fuel. The effectiveness of this price advantage can be expected to be diminished by air pollution control regulations.

d. South Atlantic States

Although coal accounts for about 80 percent of the thermal generation (the use of residual fuel oil is significant only in Florida), its competitive position vis-a-vis nuclear fuel is weak except for West Virginia, which is the leading coal-producing state in the Nation. In this state coal will continue to be the principal fuel for electric power generation, although a preponderance of plants along the Appalachian are converting from coal to oil. These states have also been the most successful in installing nuclear power plants in recent years.

e. East South Central States

Low-cost coal will continue to be highly competitive with nuclear fuel in Alabama, Kentucky, and Tennessee. Natural gas will prevail in Mississippi.

f. West South Central States

Practically all the thermal electric power in this area is generated with natural gas. This region, including its offshore areas, is the origin of 30 percent of the Nation's current consumption of natural gas. Gas will continue to be the principal source of primary energy for electric power generation in the foreseeable future.

g. Mountain States

The Mountain States are well-endowed with low-cost, low-sulfur coal and this fuel will remain the dominant fuel in the electric utility market of the area. In addition, significant quantities of natural gas will continue to be used in Arizona, Nevada, and New Mexico. Synthetic gas from coal gasification is expected to be competitive with LNG and methane.

h. Pacific States

Although plans are underway for the use of coal for electric power generation in this region, to date, more than four-fifths of thermal electric generation is produced with natural gas and the remainder with residual fuel oil. The cost of fossil fuels in the Pacific States, however, is generally high, and nuclear fuels should be able to compete effectively in the area, assuming that suitable sites for nuclear generation can be established.

The average cost of fossil fuels has increased noticeably in the recent past. Continued escalation is expected in the future. For the purposes of this study, fuel costs expected to occur in 1980 in the Southern Pacific and Southwestern region of the United States were emphasized. These costs can be varied to account for regional effects by using the influence coefficients provided. Fuel costs, in cents/10^6 BTU, are shown in Table B-4 where they are converted to mills/kWh for each of the competing systems. The sources for the data are given in the table. The oil/gas-fired steam plant fuel costs are based on the projected cost of oil. It is assumed that gas prices will be adjusted upward to be comparable to oil prices.

Fuel cost influence coefficients are given in Table B-5. These can be used to determine fuel cost changes from the nominal with change in the parameters of interest. Since the fuel cost is nonlinear with respect to efficiency, the efficiency influence coefficient is valid only for small efficiency changes about the nominal. Thus care should be exercised in using this influence coefficient. The alternative system efficiencies were previously presented in paragraph D of this Appendix.

Table B-4. Alternative system fuel costs (1000 MW plants; reference year 1980)

Parameter	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
Fuel Cost, ¢/10^6 BTU	40[1, 2]	90 (Oil)[1]	40 (Coal)[1, 2]	105 (Dist. Oil)	40 (Coal)[1, 2] 90 (Oil)[1]	24[1, 2]	24[1, 2]	10[1, 2]
Plant Efficiency, %	40	40	50	48	48	33	39	40
Fuel Cost, mills/kWh	3.4[3]	7.7 (Oil)	2.7	7.5 (Dist. Oil)	2.8 (Coal) 6.4 (Oil)	2.5[3]	2.1	0.9

NOTES:

1. Date from private communications.
2. Reference B-6 fuel costs referenced to 1980 using 5% escalation.
3. Compares with data in Ref. B-8.

Table B-5. Alternative systems' fuel cost influence coefficients (nominal costs for 1000 MW plants, based on 1980 reference year)

Influence Coefficient	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
1. $\frac{\partial C_F}{\partial C_{fuel}} = \frac{0.0341^*}{\eta}, \frac{\text{mills BTU}}{¢\ \text{kWh}}$ (Multiply by change in C_{fuel}, $¢/10^6$ BTU, to get change in C_F, mills/kWh)	0.085	0.085	0.068	0.071	0.071	0.104	0.088	0.085
2. $\frac{\partial C_F}{\partial \eta} = -\frac{0.341\ C_{fuel}}{\eta^2}$, mills/kWh (Multiply by change in η, %/100, to get change in C_F, mills/kWh.)	-8.5	-19.2	-5.5	-15.6	-5.9 (Coal) -13.3 (Oil)	-7.5	-5.4	-2.4

$^*C_F$ = Fuel-related generation cost, mills/kWh.

C_{fuel} = Basic fuel cost, $¢/10^6$ BTU.

η = Plant efficiency, %/100.

3. Total Costs

Total costs are comprised of the fixed costs and fuel costs previously presented plus operations and maintenance costs, insurance costs and amortized research and development costs for advanced systems not yet developed. The nominal total costs are shown in Table B-6. Influence coefficients are presented in Table B-7. These can be used to establish variation from the nominal of the total power generation costs with variations of the various cost parameters.

The operations and maintenance (O & M) costs shown in Table B-6 for the conventional steam plants (fossil fuel and nuclear) and the gas turbine binary plant were obtained from private communications with industry. The coal-fired steam plant O & M costs are higher primarily due to repair and maintenance of coal handling equipment exposed to heavy duty, ash handling, fuel storage, etc. The O & M costs for the coal-fired plasma MHD binary plant were assumed to be slightly higher than the steam plant due to the added complexity of the MHD system and the need to replace the channel. Similarly the fast breeder reactor plant was assumed to have a slightly higher O&M cost than the light water nuclear reactor plants. The oil-fired potassium Rankine binary system was assumed to have slightly higher O&M costs than the gas turbine binary plant; the coal-fired potassium Rankine binary plant was assumed to have O&M costs slightly higher than the coal-fired steam plant.

Insurance covering liability to personnel at the nuclear plant sites is included for all nuclear plants. The approximate annual nuclear insurance cost is one million dollars for a plant having an electrical output of 1000 MW (Ref. B-9). This also compares with insurance data presented on page 87 of Ref. B-10.

Amortized research and development (R&D) costs have been estimated as follows. It has been estimated that the development of an advanced plant using fossil fuels, e.g., the gas turbine/fossil fuel binary plant, would require about $150/kW added cost for the demonstration plants. If one small (150 MW) and three 1000 MW demonstration plants are built, the R&D costs would total about $500 million. From Appendix A, the projected new plant requirements were 16-1000 MW fossil fuel and 35-1000 MW nuclear plants per year.

Table B-6. Alternative system total costs

Cost Parameter	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
Fixed Cost	7.3	4.9	7.4	6.3	7.4 (Coal) 5.7 (Oil)	8.6	8.6	10.75
Fuel Cost	3.4	7.7 (Oil)	2.7	7.5 (Dist. Oil)	2.8 (Coal) 6.4 (Oil)	2.5	2.1	0.9
Operating & Maintenance Costs	0.9[1]	0.5[1]	1.0[2]	0.75[1]	1.0[3] (Coal) 0.8[4] (Oil)	0.35[1]	0.35[1]	0.4[2]
Insurance Costs	--	--	--	---	--	0.1	0.1	0.1
Research & Development Costs	--	--	0.1	0.1	0.1	--	--	0.1
Total Costs	11.6	13.1 (Oil)	11.2	14.65 (Dist. Oil)	11.3 (Coal) 13.0 (Oil)	11.55	11.15	12.2

(1) O & M costs for conventional plants averaged from data from private communications.

(2) O & M costs for advanced systems estimated to be higher than conventional systems.

(3) O & M costs assumed to be slightly higher than the coal-fired steam plant.

(4) O & M costs assumed to be slightly higher than Gas Turbine Binary Cycle.

Table B-7. Alternative systems' total cost influence coefficients (nominal costs for 1000 MW plants, based on 1980 reference year)

Parameters	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/ Fossil Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Thermal Nuclear Reactor	Liquid Metal Fast Breeder Reactor
1. $\frac{\partial C_G}{\partial C_C} = \frac{10\ F}{H}$, $\frac{\text{mills}}{\$\ \text{h}}$ (Multiply by change in C_C, \$/kW, to get change in C_G, mills/kWh.)	0.0228	0.0214	0.0245	0.0228	0.0228 (Coal) 0.0221 (Oil)	0.0214	0.0214	0.0214
2. $\frac{\partial C_G}{\partial F} = \frac{10\ C_C}{H}$, $\frac{\text{mills yr}}{\text{kWh}}$ (Multiply by change in F, %/yr, to get change in C_G, mills/kWh.)	0.486	0.382	0.49	0.411	0.495 (Coal) 0.384 (Oil)	0.570	0.570	0.713
3. $\frac{\partial C_G}{\partial H} = -\frac{10\ C_C F}{H^2}$, $\frac{\text{mills yr}}{\text{kWh}^2}$ (Multiply by change in H, h/yr, to get change in C_G, mills/kWh.)	-1.11×10^{-3}	0.70×10^{-3}	-1.20×10^{-3}	-0.94×10^{-3}	-1.13×10^{-3} (Coal) -0.87×10^{-3} (Oil)	-1.22×10^{-3}	-1.22×10^{-3}	-1.5×10^{-3}
4. $\frac{\partial C_G}{\partial C_{fuel}} = \frac{0.0341}{\eta}$, $\frac{\text{mills BTU}}{¢/\text{kWh}}$ (Multiply by change in C_{fuel}, $¢/10^6$ BTU to get change in C_G, mills/kWh.)	0.085	0.085	0.068	0.071	0.071	0.104	0.088	0.085
5. $\frac{\partial C_G}{\partial \eta} = \frac{0.0341\ C_{fuel}}{\eta^2}$, mills/kWh (Multiply by change in η, %/100, to get change in C_G, mills/kWh.)	-8.5	-19.2	-5.5	-15.6	-5.9 (Coal) -13.3 (Oil)	-7.5	-5.4	-2.4

C_G = Power Generation Cost, mills/kWh; F = Fixed Charge, %/yr; H = Average Hours on Line Per Year, h/yr

C_C = Capital Cost, \$/kW; C_{fuel} = Fuel Cost, $¢/10^6$ BTU; η = Plant Efficiency, %/100

If it is assumed that about one-fourth of the new fossil fuel plants constructed per year are advanced plants, the amortized R&D costs (20-year amortization period and 75% capacity factor) are about 0.1 mills/kWh. For the liquid metal fast breeder reactor the added R&D costs have been estimated to be 2 to 3 times as great as that estimated above for advanced fossil fuel plants (Ref. B-14). But the number of plants to be built will be substantially greater and thus the amortized R&D cost of 0.1 mills/kWh is used for it also. If different numbers of advanced plants are actually built, or if a different amortization period is used, the above number will, of course, change. For the purposes of this study 0.1 mills/kWh is added to advanced plants for amortized R&D costs.

Examination of the influence coefficients in Table B-7 shows the following:

1) Since the annual fixed charge was the same for all systems and the full load capacity factors varied only a little, the effect of changes in capital cost on total cost is about the same for all systems. The generation cost of the open cycle plasma MHD/fossil fuel steam system is seen to be most affected by changes in capital cost due to the lower capacity factor assumed for this system.
2) Changes in financial charge will affect the generation cost most for the systems having the higher capital costs. Compare, for example, the influence coefficient for the liquid metal fast breeder reactor (LMFBR) with the other systems.
3) Changes in capacity factor (hours on line per year) affect generation costs more for systems having high capital costs and/or low capacity factors, e.g., the nuclear systems and the open cycle plasma MHD/fossil fuel binary plant.
4) Changes in generation cost due to changes in fuel cost are a function of plant efficiency; the greatest effect occurs with plants having low efficiency.
5) Efficiency change has the greatest effect on the generation cost of plants having high fuel cost and/or low efficiency. Note the large effect efficiency changes have for oil-fired plants, and the small effect it would have for the LMFBR.

Figure B-2 is a plot of the nominal total costs as a function of fuel costs. The lines drawn through each nominal value show the generation cost trends with changes in fuel costs. Note the similarity of the curves, indicating the small relative cost effect on plants using the same fuel; absolute cost changes with fuel cost changes are significant, however. The nominal costs shown can be expected to vary as much as 15-20 percent due to possible changes in capital costs and fuel costs resulting from alternative site locations, inflation, environmental control pressures, etc. Capital cost variations alone as predicted in Ref. B-7 would result in 10% variation in nominal values. The relative cost accuracy would be less, however, since all plants would be subject to similar changes in labor rates, fuel costs, annual carrying charge, etc. The figure reveals the following:

1) Of the conventional plants, the coal-fired steam, light water nuclear reactor and gas-cooled nuclear reactor systems have the lowest costs, and for this reason they are employed as base loading plants. (Relative changes in fuel cost or capital costs, or fuel availability could change this.)
2) The liquid metal fast breeder reactor is potentially competitive for full-capacity base loading.
3) Oil-fired steam plants have higher generation costs than nuclear or coal-fired steam plants due to the cost of fuel and are thus relegated to swing plant usage, unless environmental pressures or fuel availability preclude the use of coal-fired systems.
4) The coal-fired potassium Rankine/steam plant and plasma MHD/ steam plant have potential 1980 generation cost reductions of 0.3 to 0.4 mills/kWh compared with conventional coal-fired plants.
5) The oil-fired potassium Rankine/steam plant has a slight (about 0.1 mill/kWh) potential cost reduction compared with conventional oil plants.
6) The gas turbine/steam plant, although also capable of achieving improvements in performance, suffers from the need to use expensive fuels and thus has the highest generation cost calculated.
7) The generation costs of the three advanced binary plants could be reduced as a result of technology improvements. These are discussed in section 2 following.

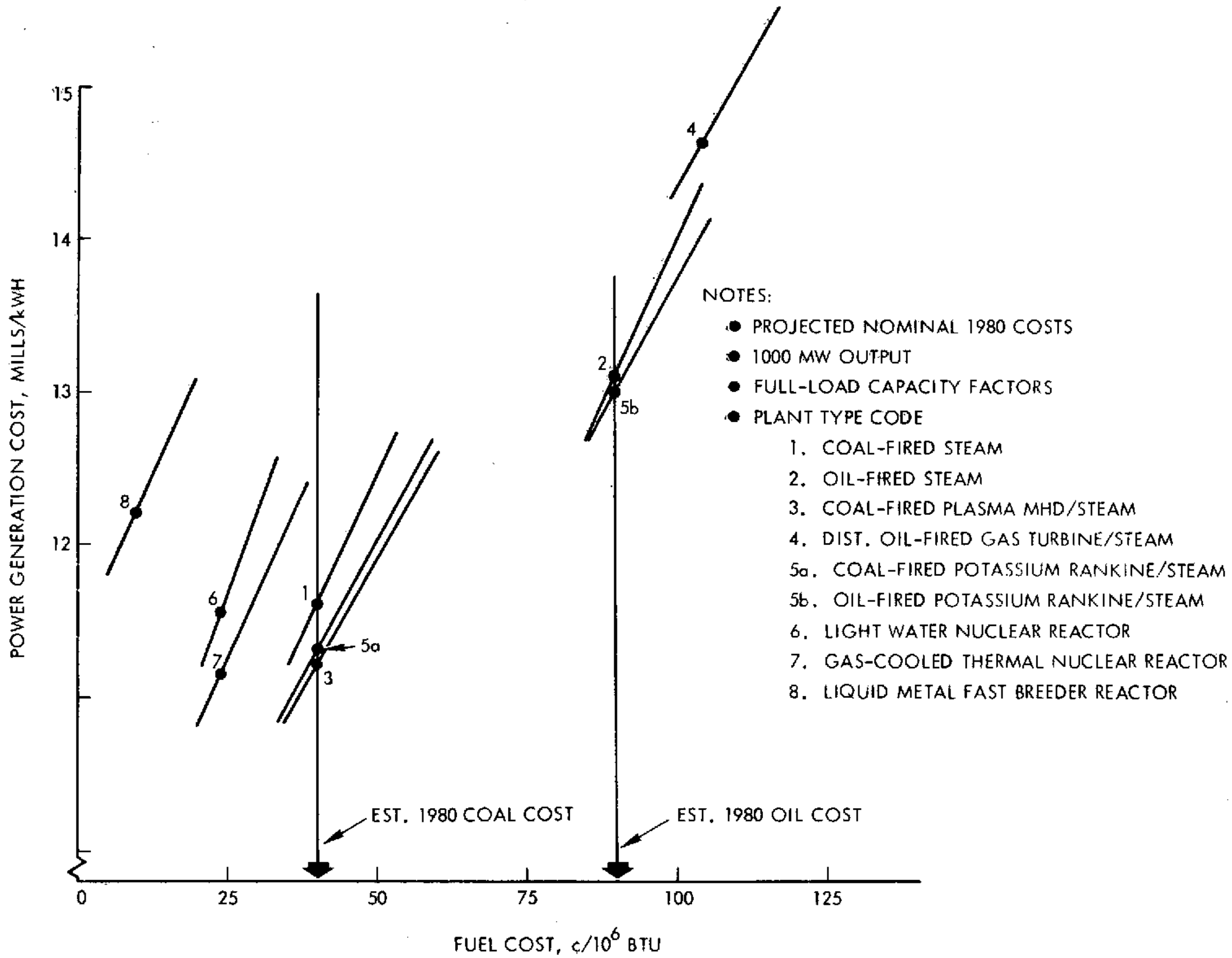


Fig. B-2. Alternative systems' generation cost

4. Alternative Fuel Scenarios

The above analysis considered that there would be no drastic restrictions on fuel availability and that the use of alternative fuels would be governed primarily by economic factors. There are other pressures, however, which could affect the use of the alternative fuels, such as environmental restrictions and import limitations. Possible alternative fuel scenarios and the effect on power plant selection are postulated in Appendix F, paragraph D-6.

5. Technology Improvements

The technology status (efficiency) assumed for the advanced alternative systems is considered consistent with the liquid metal MHD technology assumptions used in this study. However, it is possible that improvements in technology, not considered in the previous analyses, could result in higher efficiencies for the gas turbine/steam binary plant and the potassium Rankine/steam binary plant. Also, it is possible that technology could be developed to allow assumption of a higher capacity factor for the plasma MHD/steam plant than was previously used in the analysis. The effect on total cost of assuming improved performance for the above three systems is established here. Table B-8 shows the efficiencies and capacity factors for the three advanced plants, and the corresponding generation cost determined from the influence coefficients of Table B-7.

By comparing the costs in Table B-8 with the costs in Table B-6 the following conclusion can be drawn:

1) The gas turbine/steam binary system is still the most costly system due to the need to use expensive fuel and its relative position would only change if fuel costs for other systems increased significantly from those used in this report.
2) The coal-fired plasma MHD/steam binary plant has become significantly less costly than the coal-fired and nuclear steam plants (about 1 mill/kWh) due mainly to the increased capacity factor. The feasibility of achieving the performance given in Table B-8, however, is in question.

Table B-8. Cost effects of technology improvements for selected advanced alternative systems (1980 costs, 1000 MW plants)

Advanced Alternative Systems	Capacity Factor, %		Efficiency, %		Generation Cost, Mills/kWh	
	Baseline Value	New Value	Baseline Value	New Value	Baseline Value	New Value
1. Open Cycle Plasma MHD/ Fossil Fuel Steam	70	75	50	55	11.2	10.5
2. Gas Turbine/Fossil Fuel Steam	75	75	48	52	14.65	14.0
3. Potassium Rankine/Fossil Fuel Steam	75	75	48	51	11.3 13.0	11.1 (Coal) 12.6 (Oil)

3) The potassium Rankine/steam binary system now has a generation cost about 0.5 mills/kWh lower than conventional fossil-fuel plants. The improvement relative to the oil-fired system, when compared with the data of Table B-6, was greater than the improvements relative to the coal-fired system due to the more significant efficiency effect for systems utilizing high cost fuels.

F. ALTERNATIVE SYSTEM ENVIRONMENTAL EFFECTS

Environmental effects in this study are considered only to the extent that addition of a liquid metal MHD topping cycle causes a change. Consequently, the effects of fuel mining and transportation (oil spills, etc.) are not considered. Alternative systems' environmental effects, primarily due to the plants themselves, are presented here for use in the comparative analysis (Appendix F). The relative importance of environmental impacts, which the competing systems present via the atmosphere, surface waters and land surfaces, is exemplified by the data presented as follows:

1. Air Pollution

Table B-9 (data from Ref. B-11) shows the pollutant formation and annual release from a typical 1000 MW plant. Conventional coal-, oil- and gas-fired plants are shown in Table B-9(a). The air pollutant emissions from a coal-fired plant are conspicuously significant and can be traced to the ash and sulfur content of the fuel and the efficiency of combustion. The use of oil- and gas-fired facilities significantly reduce the air pollutant emissions. Table B-9 presents pollutant emissions expected from the operation of a representative 1000 MW installation of gas turbines burning gas, oil, or jet fuel.

Fossil fuel emission factors are presented, per unit of fuel, in Table B-10, based on data from Ref. B-6. These values take into account current and future EPA standards where appropriate. The total production of air pollutants per year for all plants of various types as a function of future years is shown in Table B-11 (Ref. B-6). The predictions of Table B-11 are based on plant projections presented in Ref. B-6.

For the advanced open cycle plasma MHD/steam and potassium Rankine/steam binary plants, the air pollutants, except for NO_X, will be reduced per KW of electricity generated, with respect to conventional plants, in proportion to their increase in efficiency (paragraph D, Appendix F). NO_X production is a function of temperatures and residence times at high temperature. Thus systems operating at high temperatures, particularly the plasma MHD/steam system, will have higher NO_X production than shown in Tables B-9, B-10 and B-11.

2. Nuclear Pollution

The following is a direct quote from Reference B-6 on radiation pollution.

"The radiation dose to the population from normal operation of nuclear power plants is determined, as an upper bound, by the standards set for the permissible dose at the plant boundaries. New regulations currently under review would limit off-site doses to 5 mrem per year, a factor of 100 lower than those currently in effect. Current practice is consistent with such a limit.

Table B-9. (a) Air pollutant emissions from a typical 1000 MWe conventional power plant[1, 2]

Pollutant	Annual Release (10^6 lb)		
	Coal[3]	Oil[4]	Gas[5]
Particulates	9.9	1.6	1.02
Oxides of sulfur	306.0	116.0	0.027
Oxides of nitrogen	46.0	47.8	26.6
Carbon monoxide	0.460	0.0184	Negligible
Hydrocarbon	1.150	1.47	Negligible

(b) Approximate annual gas turbine emissions for 1000 MWe[1]

Pollutant	Annual Release (10^6 lb)[6]
Particulate Carbon	2.5-6
Particulate Ash	Negligible
Oxides of sulfur	25
Oxides of nitrogen	25-160
Carbon monoxide	5-400
Hydrocarbon (other than carbon)	1

1. Ref. B-11.
2. Based on normal average heat rates, load factors, and fuel properties.
3. Burning 2.3 x 10^6 tons/year. Assuming 3.5% sulfur content of which 15% remains in the ash, and a 9% ash content with 97.5% fly ash removal efficiency.
4. Burning 460 x 10^6 gallons/year. Assuming 1.6% sulfur content and 0.05% ash content.
5. Burning 68 x 10^9 sulfur-content fuel/year.
6. For #2 distillate oil, sulfur content 0.2%, full load conditions, heat rate 15,000 BTU/kW.

Table B-10. Air pollution emission factors for fossil fuels[1]

Parameters	CO_2	CO	SO_2[2]	NO_X	Particulates	Hydrocarbons	Aldehydes
Electric Utilities - Existing							
Oil (Residual)							
($lb/10^3$ Gal)		0.04	157 S	105	8	2.0	1.0
($lb/10^6$ BTU)	170	0.0002	1.047 S	0.700	0.054	0.013	0.007
Coal (Bituminous)(lb/ton)		1.0	38 S	20	26[3]	0.3	0.005
($lb/10^6$ BTU)	224	0.040	1.529 S	0.81	1.054	0.0121	0.0002
Gas ($lb/10^6$ ft^3)		0.4	0.6	390	15	40	3
($lb/10^6$ BTU)	122	0.000387	0.00058	0.378	0.0145	0.0387	0.0029
Electric Utilities - New Plant							
Oil (Residual)($lb/10^6$ BTU)	170	0.0002	0.8[4]	0.30[4]	0.054[4]	0.013	0.007
Coal (Bituminous)							
($lb/10^6$ BTU)	224	0.040	1.2[4]	0.70[4]	0.20[4]	0.0121	0.0002
Gas ($lb/10^6$ BTU)	122	0.000387	0.00058	0.20	0.0145	0.0387	0.0029

(1) Emission factors are from Ref. B-12, unless indicated otherwise. Table from Ref. B-6.

(2) S stands for percentage of sulfur in fuel.

(3) Given by $2A(1-\eta)$, where A-10 and η-0.8.

(4) From EPA standards, Federal Register (Ref. B-50).

Table B-11. Annual production of air pollutants[1]

Year	Fossil Fuel Plant Type	Air Pollutants[2]						
		CO_2	CO	SO_2	NO_X	Particulates	Hydrocarbons	Aldehydes
		10^{12} lb/yr	10^9 lb/yr					
1969	Gas	0.439	0.001	0.002	1.36	0.052	0.139	0.010
	Oil	0.272	0.0003	3.85	1.12	0.086	0.021	0.011
	Coal	1.66	0.297	31.8	6.02	7.83	0.090	0.001
1977	Gas	0.466	0.002	0.002	1.17	0.055	0.148	0.011
	Oil	0.529	0.001	2.46	1.68	0.168	0.040	0.022
	Coal	2.14	0.383	11.9	7.32	6.81	0.115	0.002
1985	Gas	0.437	0.001	0.002	0.939	0.052	0.138	0.011
	Oil	0.670	0.001	3.13	1.73	0.213	0.051	0.028
	Coal	2.57	0.458	14.03	8.47	5.72	0.139	0.029
2000	Gas	0.476	0.002	0.002	0.78	0.057	0.151	0.011
	Oil	0.928	0.001	4.37	1.64	0.295	0.071	0.038
	Coal	4.37	0.781	23.42	13.7	3.9	0.236	0.004

[1] Includes production attributable to energy conversion only. Industrial process emissions that are not related to fuel combustion are not included here (Ref. B-6).

[2] Based on emission factors given in Table B-10.

At these relative low exposure levels, the quantity of interest is the total accumulated dose to the population in man-rems. The new limits would correspond to a dose of about 400 man-rems per year per 1000 MWe installed capacity. In 1969 the actual population dose corresponded to less than half that amount. (The average dose to those living within 50 miles of a nuclear plant was calculated to be 0.01 mrem/year.) In any event, the resultant dose, either now or projected, is low compared to that due to natural background."

"Of more long-term significance is the KR-85 and tritium produced in the nuclear reactors and released primarily at the reprocessing plants. The total amount of high-level radioactive waste is also a potential major concern. The unit production rates for these materials are shown in Table B-12 for light water reactors (LWR's) and liquid metal cooled fast breeders (LMFBR's)." Radioactive materials produced/year are also shown in Table B-13 (Ref. B-11). The data in the two tables are from two different references, giving the data in somewhat different form and for different years. The data for solid high level wastes from the two references are consistent. The radioactive materials production data in Table B-14 is based on data presented in Table B-12.

Cumulative Kr-85, Tritium and high level solid wastes from Ref. B-6 are shown in Figs. B-3, B-4 and B-5.

3. Heat Rejection

A universal problem confronted by both the nuclear or fossil-fueled electric power plants is heat rejection and, depending upon site constraints, the incorporation of heat dissipation techniques can represent a sizeable capital investment. Heat rejection requirements for representative power generation cycles are presented in Table B-15 along with corresponding efficiencies and heat rates. The once-through cooling water requirement listed assumes a 15°F temperature rise. The management of heat dissipation, of course, can be uniquely handled, depending upon site selection, to benefit the local environment. Probable applications include heating of homes or greenhouses, desalinization of sea water, agricultural and aquacultural applications, recreation, etc.

Table B-12. Environmental effects of nuclear power plants[1]

Effect	Quantity/1000 MWe-yr		Basis
	LWR[2]	LMFBR[3]	
Population exposure due to normal releases	588 man-rem[4]	588 man-rem[4]	Proposed standards
Kr-85 production[5]	5.3×10^5 Ci	1.0×10^5 Ci	2.9×10^{-3} atoms/U-235 thermal fission 0.79×10^{-3} atoms/Pu-239 fast fission
Tritium production	1.9×10^4 Ci	2.7×10^4 Ci	Production of fuel rods at the rate of: 1.2×10^{-4} atoms/U-235 fission 2.5×10^{-4} atoms/Pu-239 fission
High level waste			
As liquid	1.0×10^4 gal	0.91×10^4 gal	100 gal/10,000 MWd(th)
As solid	110 ft^3	91 ft^3	1 ft^3/10,000 MWd(th)

(1) Ref. B-6.

(2) LWR burnup = 33,000 MWd(th)/MT, efficiency = 0.33

(3) LMFBR average burnup = 33,000 MWd(th)/MT, efficiency = 0.40

(4) Based on 400 man-rem/1000 MWe installed capacity and 0.68 load factor.

(5) For storage in salt formations, 110 ft^3 of high level waste requires approximately 0.3 acres of salt area.

Table B-13. Estimated high level waste from the civilian nuclear power industry (Ref. B-11)

	Calendar Year			
	1970	1980	1990	2000
Installed Capacity, 10^3 MW_e	6	150	450	940
Spent Fuel Processed, Metric Tons/yr	55	3,000	9,000	19,000
Volume of High-Level Liquid Waste				
Annual Production 10^6 gal/yr	0.017	0.97	3.3	5.8
Accumulated, 10^6 gal (if not solidified)	0.4	4.4	29	77
Volume of High-Level Waste, if solidified				
Annual Production 10^3 ft^3/yr	--	9.7	33	58
Accumulated, 10^3 ft^3	--	44	290	770

Table B-14. Production of radioactive materials (Ref. B-6)

Year	Plant Type	Radioactive Materials			
		T 10^6 Ci/yr	Kr 10^6 Ci/yr	Solid High Level Wastes 10^3 ft^3/yr	Exposure to Population 10^3 man-rem/yr
1969	LWR	0.028	0.784	0.163	0.870
1977	LWR	1.11	31.1	6.45	34.4
1985	LWR	3.19	88.9	18.5	98.6
2000	LWR	5.03	140.4	29.1	155.7
	LMFBR	7.40	28.5	24.9	162.3

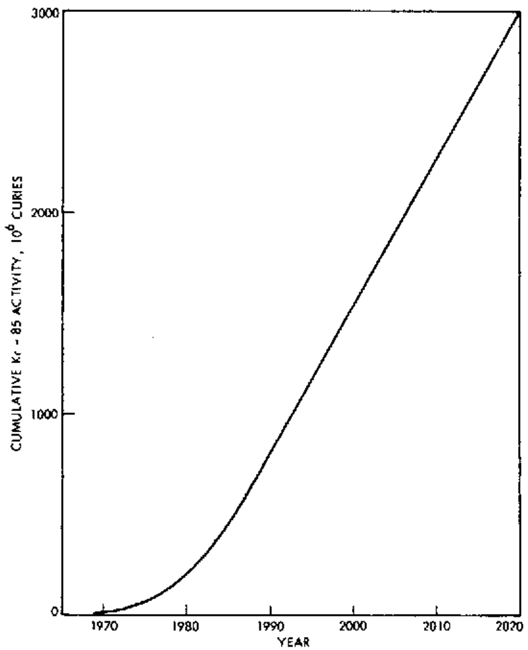


Fig. B-3. Cumulative Kr-85 activity, corrected for decay (Ref. B-6)

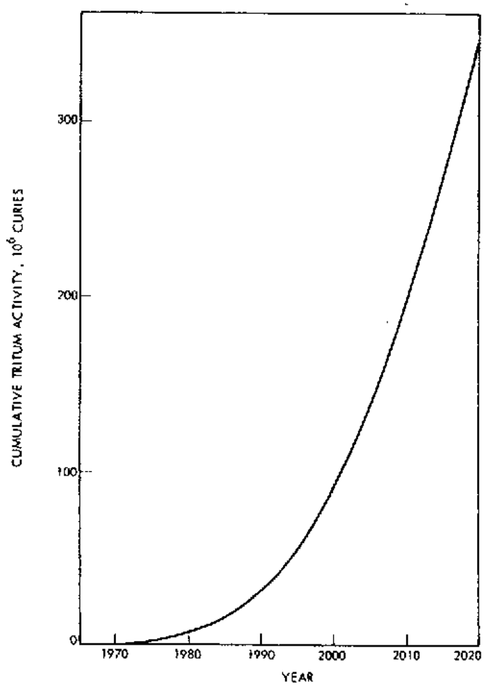


Fig. B-4. Cumulative Tritium activity corrected for decay (Ref. B-6)

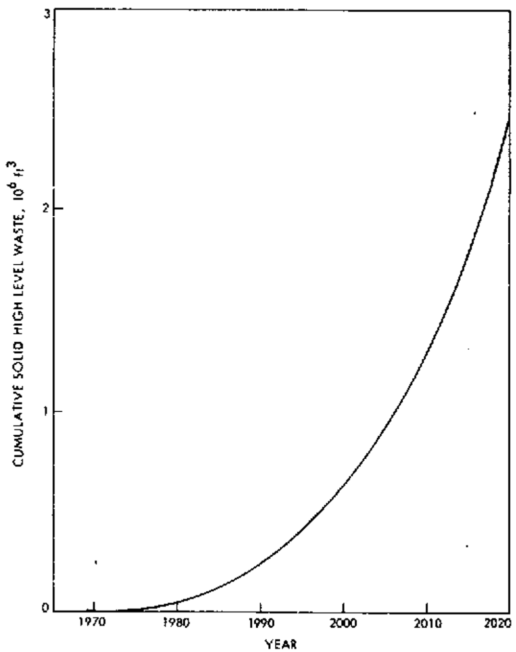


Fig. B-5. Cumulative solid high level waste (Ref. B-6)

Table B-15. Heat rejection

System	Efficiency (%)	Heat Rate (BTU/kWh)	Once-Through Cooling Water(1) (gal/kWh)
Present Nuclear Reactor	33	10, 342	55
Conventional Steam Power-plant	40	8, 533	40
High Temperature Gas Cooled Reactor	40-50	8, 533-6, 205	40-30
Advanced Nuclear	40	8, 533	40
Open Cycle MHD	55	5, 641	30
Gas-Steam Combined Cycle (Hydrogen Cooled Blades)	40-55	8, 533-5, 641	40-30
Fusion Direct Cycle	50-80	6, 205-3, 878	33-21

(1) Assumes 15° F temperature rise.

4. Land Use

Average land use for various plant types is shown in Table B-16 from Ref. B-6. Cumulative land use for different plant types is shown in Table B-17, based on plant use projections from Ref. B-6.

G. OTHER CHARACTERISTICS OF ALTERNATIVE SYSTEMS

Some of the other alternative system characteristics which have been considered and which will be used in the evaluation of the liquid metal MHD-steam binary system are: lead time, development schedule for presently undeveloped systems, and technological growth potential. Table B-18 summarizes aspects of these other characteristics for the alternative systems. A brief description of these characteristics is given as follows.

1. Reliability, Maintainability and Safety

It was beyond the scope of this study to consider reliability, maintainability and safety of the alternative systems.

Table B-16. Land use (Ref. B-6)

Use	Amount	Basis
Power Plants		3-1000 MWe plants at same site.
Coal	1.6 mi^2/1000 MWe	On-site coal storage and ash disposal
Oil	0.40 mi^2/1000 MWe	Adequate on-site fuel storage
Gas	0.24 mi^2/1000 MWe	Pipeline delivery and modest on-site fuel storage
Nuclear	0.47 mi^2/1000 MWe	Based on exclusion area requirements
Electrical Transmission	19 mi^2/1000 MWe	Projected transmission line right-of-way and electrical capacity requirements for 1990

Table B-17. Cumulative land use,(1) 10^3 square miles

	1969	1977	1985	2000	2020
Central station electric plant sites(2)					
Coal fired	0.229	0.325	0.400	0.715	1.712
Oil fired	0.016	0.024	0.031	0.450	0.250
Gas fired	0.019	0.019	0.019	0.022	0.021
Nuclear	0.002	0.042	0.121	0.390	1.026
Subtotal	0.266	0.410	0.571	1.577	3.009
Electric transmission	5.035	8.265	12.635	28.082	64.600

(1) Based on land use factors in Table B-16. Ref. B-6.

(2) Does not include hydroelectric, gas turbine, or internal-combustion plant sites.

Table B-18. Other characteristics of alternative systems

Characteristic	Coal-Fired Steam	Oil/Gas-Fired Steam	Open Cycle Plasma MHD/ Fossil-Fuel Steam	Gas Turbine/Fossil-Fuel Steam	Potassium Rankine/ Fossil-Fuel Steam	Light Water Nuclear Reactor	Gas-Cooled Nuclear Reactor	Liquid Metal Fast Breeder Reactor
1. Reliability Ranking[1]	3	2	7	5	6	1	1	4
2. Safety Ranking[2]	1	1	2	1	3	1	1	4
3. Lead Time, Years[3]	7	6	7	4	7	8-10	8-10	8-10
4. Commercialization Date	Available	Available	Mid 1980's[4]	Available Advanced Systems - 1980	Early 1980's	Available	Available	1986[4]
5. Technological Growth Potential								
a. From the present state-of-the-art	Small	Small	Undeveloped-substantial improvement possibility	Significant efficiency gains and cost reductions possible	Undeveloped-substantial improvement possibility	Small	Small	Undeveloped-substantial improvement possibility
b. From the state-of-the-art assumed in this Appendix	Small	Small	Potential efficiency and cost gains	Potential efficiency gains and cost reductions	Potential efficiency and cost gains	Small	Small	Small

NOTES:

1. Ranking based on 1 being most reliable.
2. Ranking based on 1 being the safest.
3. Based on data from private communications.
4. Reference B-14.

2. Lead Time

Lead times as shown in Table B-18 were obtained industry sources for fossil fuel plants, light water nuclear reactor plants and gas turbine combined cycle plants. It has been assumed that all nuclear plants, once they have been accepted, would have lead times the same as the light water nuclear reactor. Also, it has been assumed that the plasma MHD/steam and potassium Rankine/ steam binary plants would have lead times similar to coal-fired steam plants.

3. Development Schedules and Commercialization Dates

The following alternative systems are presently available and in use on a commercial basis:

1) Coal-fired steam.
2) Oil/gas-fired steam.
3) Gas turbine combined cycle.
4) Light water nuclear reactor.
5) Gas-cooled thermal nuclear reactor.

The presently available gas turbine combined cycle systems are for mid-range power levels and have generally lower efficiencies than given in this Appendix. The advanced systems, such as the COGAS system of United Aircraft Corporation will require 8 to 10 years to achieve the performance listed in this Appendix (Refs. B-1 and B-3). Thus, the earliest commercialization date for an advanced system would be about 1980.

Although gas-cooled thermal nuclear reactors are in use today, their use is quite limited. It is possible that these reactors will be used more extensively in the future.

The remaining three alternative systems are yet to be developed and thus their commercialization date is uncertain. If the plasma MHD/steam binary system were developed according to the development schedule given in Ref. B-14, the system could be available for commercial application in the mid-1980's.

Similarly, if appropriate development funds were made available for the potassium Rankine/steam system it could be available for commercial application in the early 1980's. A development schedule for the liquid metal fast breeder reactor was presented in Ref. B-14. Construction of demonstration plants would begin in 1972, 1974 and 1976 with commercial availability by 1986.

4. Technological Growth Potential

Technological growth potential is defined in this study as technological change of a system which produces improvements in costs, efficiency, or environmental effects. Technological growth potential is considered from two standpoints:

1) Potential growth from the present state-of-the-art.
2) Potential growth from the state-of-the-art assumed in this report.

Considering the first standpoint, the alternative systems can be categorized into two classes: developed and undeveloped. Of the developed systems there is no evidence that any technological change will produce significant improvement in system costs, except for the gas turbine/steam binary system. And whereas environmental pollution will be reduced, it will be accomplished at increased costs. Reference B-14 presented brief descriptions of technological improvements which could be made in existing and future systems.

Even though there are R&D improvements which can be made to the fossil fuel-fired steam systems, the effect on improved cost and efficiency are relatively small. Similarly, technological improvements will be made for the conventional nuclear systems, but it is unlikely that efficiencies and costs presently achieved for these systems will be improved upon. The gas turbine/steam binary system is just beginning to be applied commercially and has significant potential for improved efficiency and cost.

The other advanced systems are presently undeveloped and thus have substantial growth potential.

When considering the growth potential from the state-of-the-art assumed in this report, the three advanced binary systems have the potential of improved efficiency, above the nominal value used in the basic cost analysis. The effect of improved performance on cost of these advanced binary systems was investigated in paragraph D-5.

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APPENDIX C

SUMMARY OF TECHNOLOGY STATUS OF LMMHD SEPARATOR SYSTEMS

A. INTRODUCTION

Alternative liquid metal MHD cycles have been considered for application to central station utility power. The cycles have been reviewed and two were selected for more detailed analysis (Appendix D). Component performance capability is reviewed as background for use in the cycle analysis. Finally, the liquid metal MHD program at JPL is reviewed.

B. LIQUID METAL MHD CYCLES

The basic process which is common to all liquid metal MHD (LMMHD) cycles is the acceleration of a liquid metal to a high velocity to generate electrical power in a magnetic field. Many different thermodynamic cycles have been proposed to achieve this acceleration in a closed system operating between a heat source and heat sink. Comprehensive summaries of these cycles and the working principles have already been given (Refs. C-1 through C-5). In general, the cycles proposed have evolved from simple, single-stage systems of low efficiency to more sophisticated systems with power extraction at several stages of the acceleration process and/or regenerative heating to achieve higher levels of efficiency.

The most highly developed LMMHD systems are the two-component separator, single-component separator, injector, and emulsion flow MHD cycles. Each of these will be described; first, in its simplest, single-stage configuration and, then for the former two, in its most efficient multistage variation. Although the multistage variations may be necessary to attain the efficiency levels needed for central station power generation, other applications occur where weight, size, and simplicity are important and single-stage liquid metal MHD systems are competitive with alternative power sources. Two of these applications are power systems for space (Ref. C-6) and for deep submergence vehicles (Ref. C-7). The following summaries should provide insight into the physical processes occurring in these four cycles. Temperature-entropy diagrams are given in Refs. C-4 and C-5 and will not be repeated here.

1. Two-Component Separator Cycle

In the two-component separator cycle shown in Fig. C-1, a liquid metal with low vapor pressure (such as lithium) is heated and mixed with a liquid metal of high vapor pressure (such as cesium) resulting in a two-phase mixture. The vapor performs work on the liquid, accelerating it to high velocity in a nozzle and subsequently the liquid phase is separated from the vapor phase. The high velocity liquid phase flows through the MHD generator, producing electric power. The kinetic energy remaining after extracting the power is used to circulate the liquid through the heat source and to the mixer. The vapor, which was separated, flows to a heat exchanger where it is condensed, with the heat being rejected to either ambient or to another power cycle. The cesium is subsequently pressurized and returned to the mixer by a pump.

2. Single-Component Separator Cycle

The single-component separator cycle of Fig. C-2 uses a single liquid metal (such as potassium). This fluid is vaporized in the heat source to a low quality (mass ratio of vapor to total fluid, typically 1-5% vapor) and is expanded to a higher quality and high velocity in a nozzle. The resulting high velocity liquid is separated from the vapor and passed through the MHD generator and then returned to the heat source. The vapor is condensed and returned to the heat source by a pump.

3. Injector Cycle

The injector cycle, which usually uses a single component, is similar to the single-component separator cycle in that a liquid metal is vaporized in the heat source and expanded to a high velocity in the nozzle. In this case, as shown in Fig. C-3, an all liquid flow is attained by injecting subcooled liquid

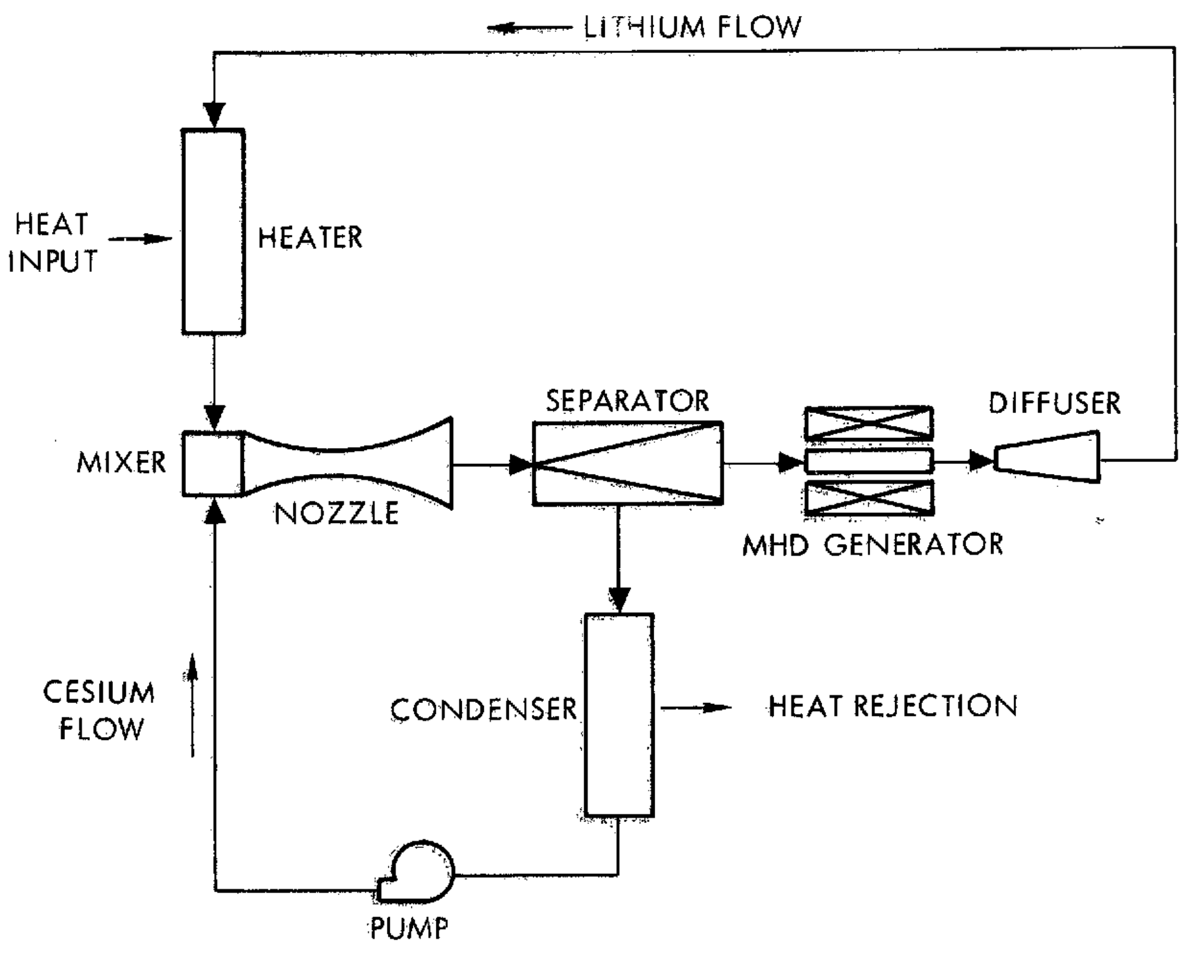

Fig. C-1. Two-component single stage separator cycle (cesium and lithium shown)

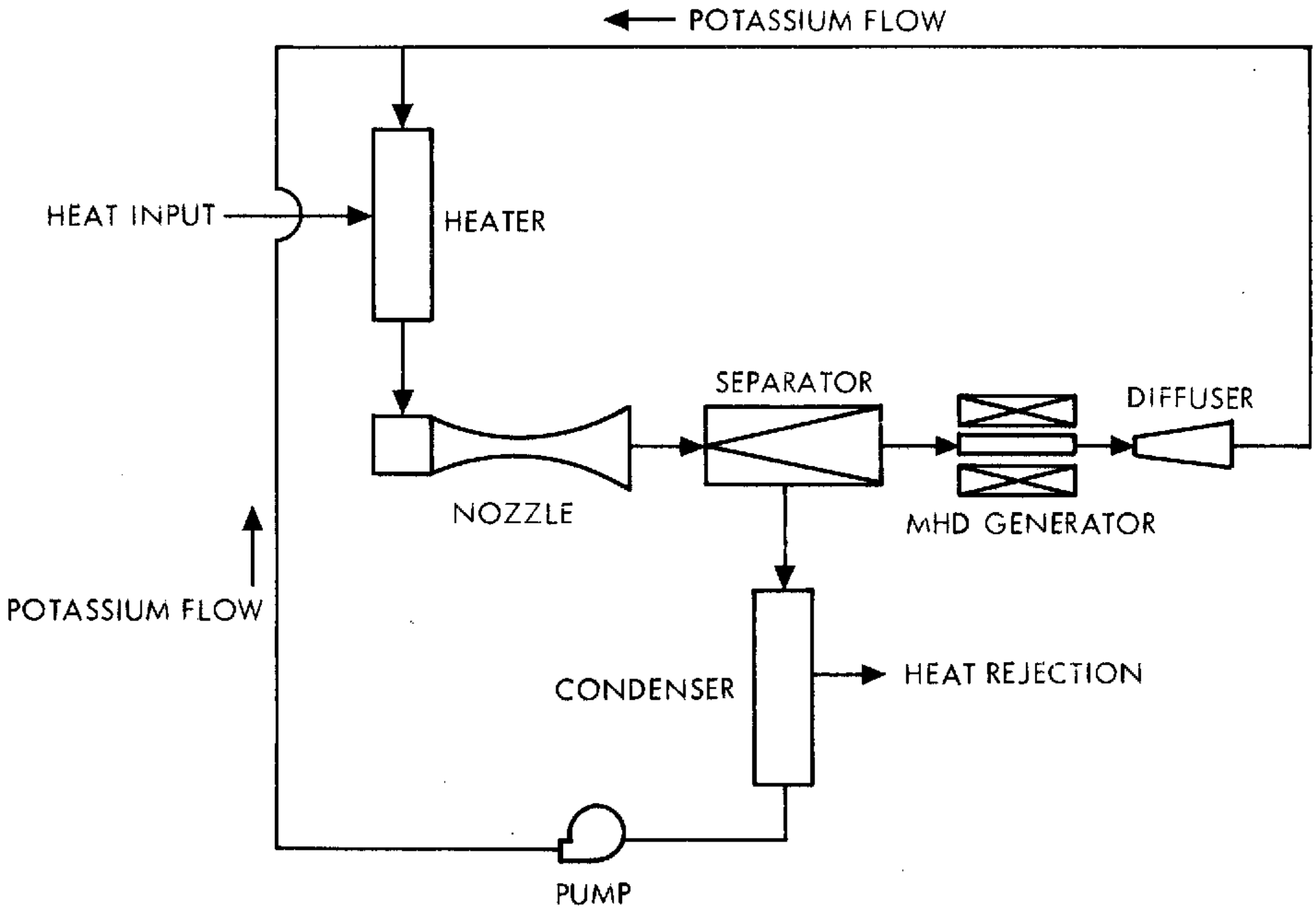

Fig. C-2. Single component, single stage separator cycle (potassium shown)

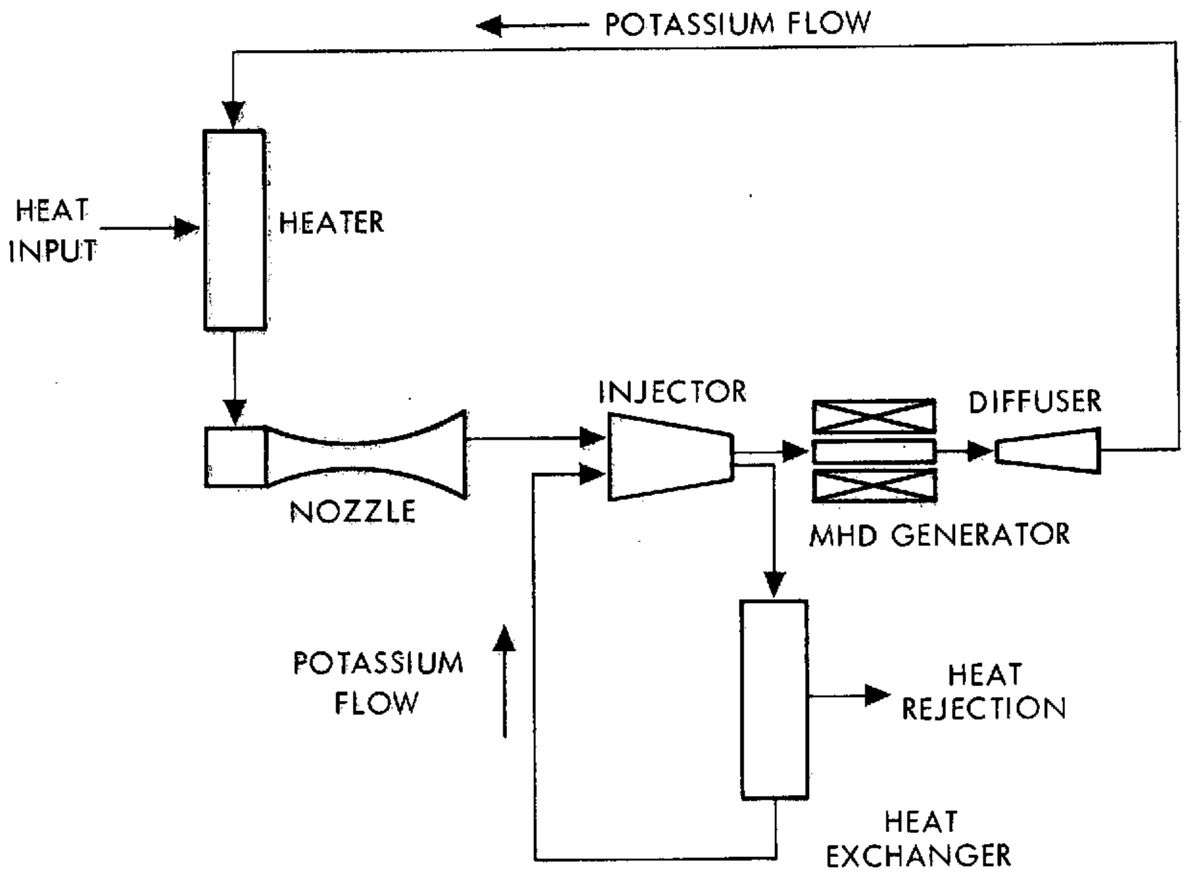

Fig. C-3. Schematic of single stage injector cycle (potassium shown) to condense the vapor phase. Part of the resulting stream flows through the MHD channel, generating electric power, and is returned to the heat source. The remainder circulates through a heat exchanger, where it is subcooled and is subsequently injected to condense the vapor.

4. Emulsion Flow Cycle

The emulsion flow cycle (Fig. C-4) uses two components -- a liquid metal (such as sodium) and an inert gas (such as helium). The liquid metal is heated and mixed with the gas at high pressure. The resulting mixture is expanded through a nozzle (which also incorporates an MHD channel), generating electric power until a void fraction of gas is reached at which the electrical conductivity is too low for power generation. The mixture is further expanded to a velocity high enough to return the liquid, when separated, through the heat source to the mixer. The gas, which was separated, flows through a heat exchanger where it is cooled and is then elevated to the peak pressure of the cycle by mechanical compressors.

5. Cycle Selection

Due to the limited scope of this study, the number of cycles analyzed had to be reduced. Of the cycles described above only the emulsion flow cycle is applicable as a primary cycle; all the others are applicable as topping cycles, but the emulsion flow cycle has calculated efficiencies lower than a conventional steam cycle for the temperature limits of a steam cycle. The emulsion flow cycle must operate at higher temperatures than the steam cycle to achieve equivalent efficiencies, and then a steam cycle with a topping cycle operating between the same temperature extremes would have a higher efficiency.

The emulsion flow cycle also has a basic problem of liquid metal freezing on the compressor blades at the lower temperatures, which might dictate the incorporation of an MHD compressor. This would reduce the presently calculated efficiencies. Therefore, the emulsion flow cycle was not considered further in the study, and analysis was limited to topping cycle applications.

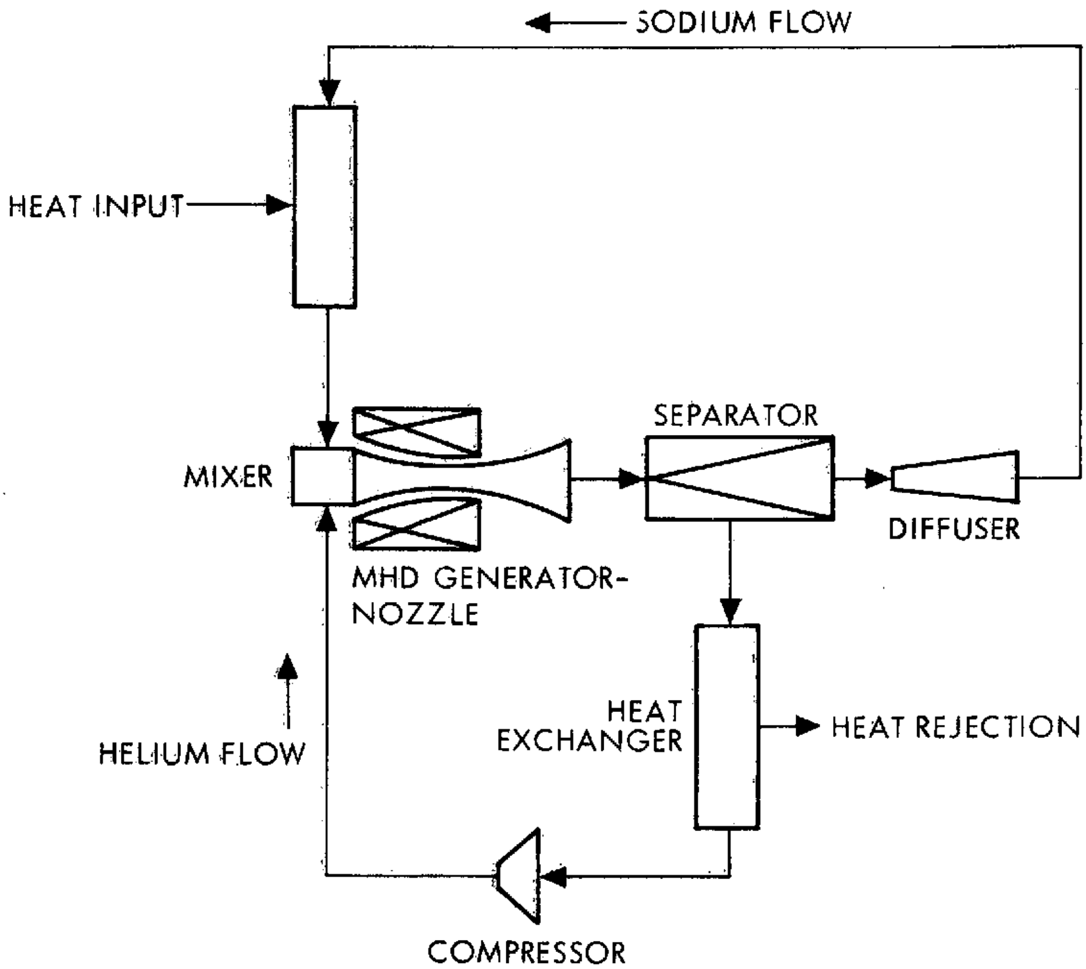

Fig. C-4. Schematic of single stage emulsion flow cycle (lithium and helium shown)

Of the remaining cycles the separator cycles have had the benefit of much greater applied research and have demonstrated adequate hydraulic performance as a power system. The injector-condenser systems, on the other hand, have not yet demonstrated adequate performance. Therefore, the separator cycles were selected for more detailed analysis in this study. Two were analyzed to determine the maximum efficiency: a multistage Cs-Li separator cycle with a small amount of regenerative heating, and a multistage potassium (K) separator cycle with extensive regenerative heating.

The multistage Cs-Li system is shown schematically in Fig. C-5 for five stages of power extraction. Lithium and cesium are mixed in the first stage nozzle and expanded to an intermediate pressure and velocity and then separated. The resulting high velocity stream of lithium passes through the first MHD generator and is then remixed with the cesium vapor from which it had been separated.

The mixture is further expanded in the second stage nozzle and the separation and power generation steps repeated. This process is continued to the last stage where sufficient dynamic pressure is retained in the lithium to return it through the heat source to the first-stage nozzle. The separated cesium vapor from the last stage flows through a regenerative heat exchanger to the condenser where it is condensed. Then it is pressurized by a pump and returned through the heat exchanger to the first-stage nozzle.

The single-stage cycle, while the simplest, has two disadvantages: all of the vapor-liquid separation occurs at the lowest pressure in the cycle resulting in a high vapor-liquid volume ratio and therefore a large separator area per unit volume of liquid; a very high velocity flow (typically 500 ft/s) is presented to the MHD generator, resulting in high frictional losses in this component. The multistage cycle obviates these difficulties by achieving a major portion of the separation at higher pressures and by presenting lower velocity flow (typically 200 to 400 ft/s) to the MHD generator.

An example of a multistage potassium separator system with regenerative heating is given in Fig. C-6. Heat is added to the liquid metal flow in the upper stage of a multistage system. This heat input results in a two-phase flow of

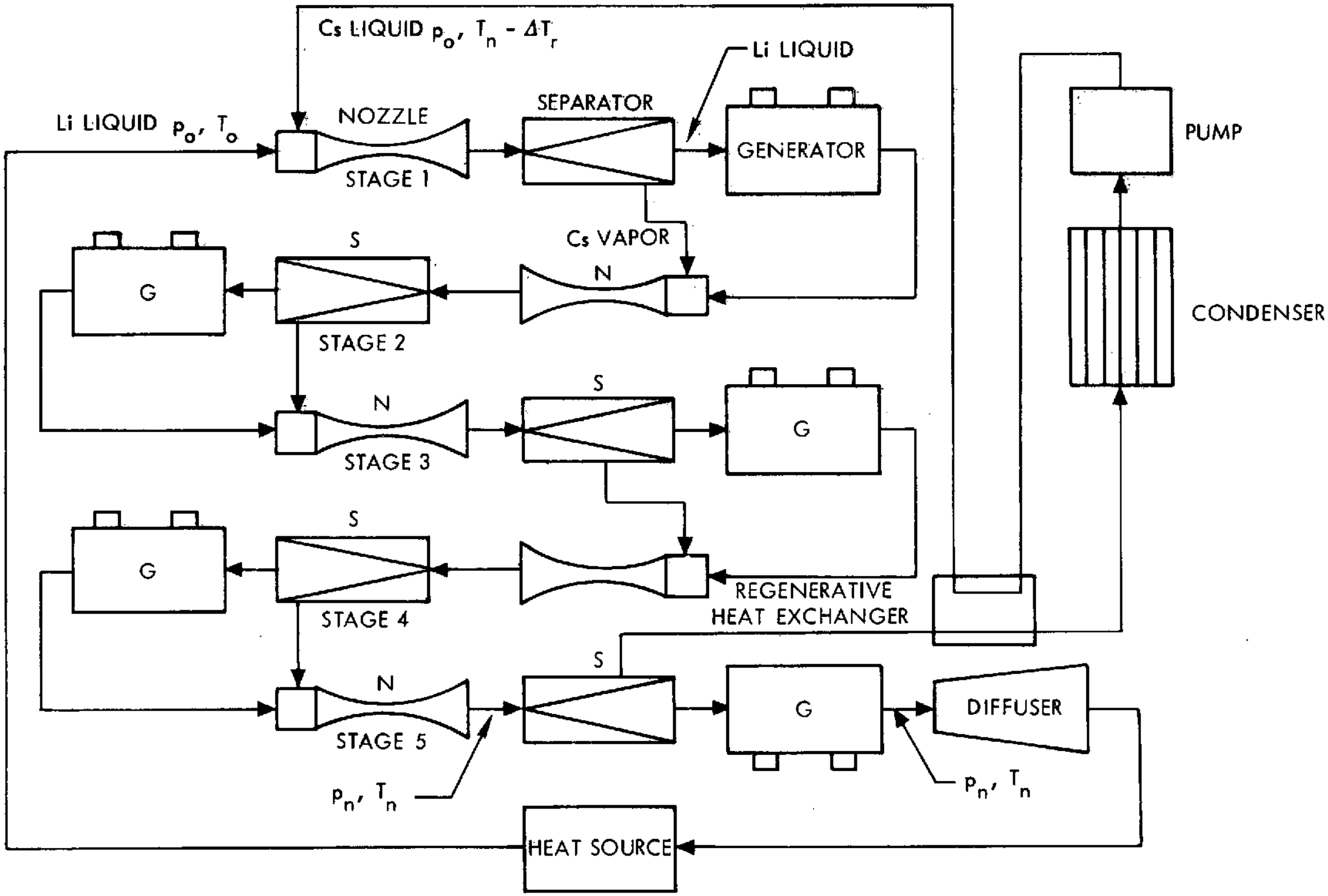

Fig. C-5. Multistage cesium-lithium separator system

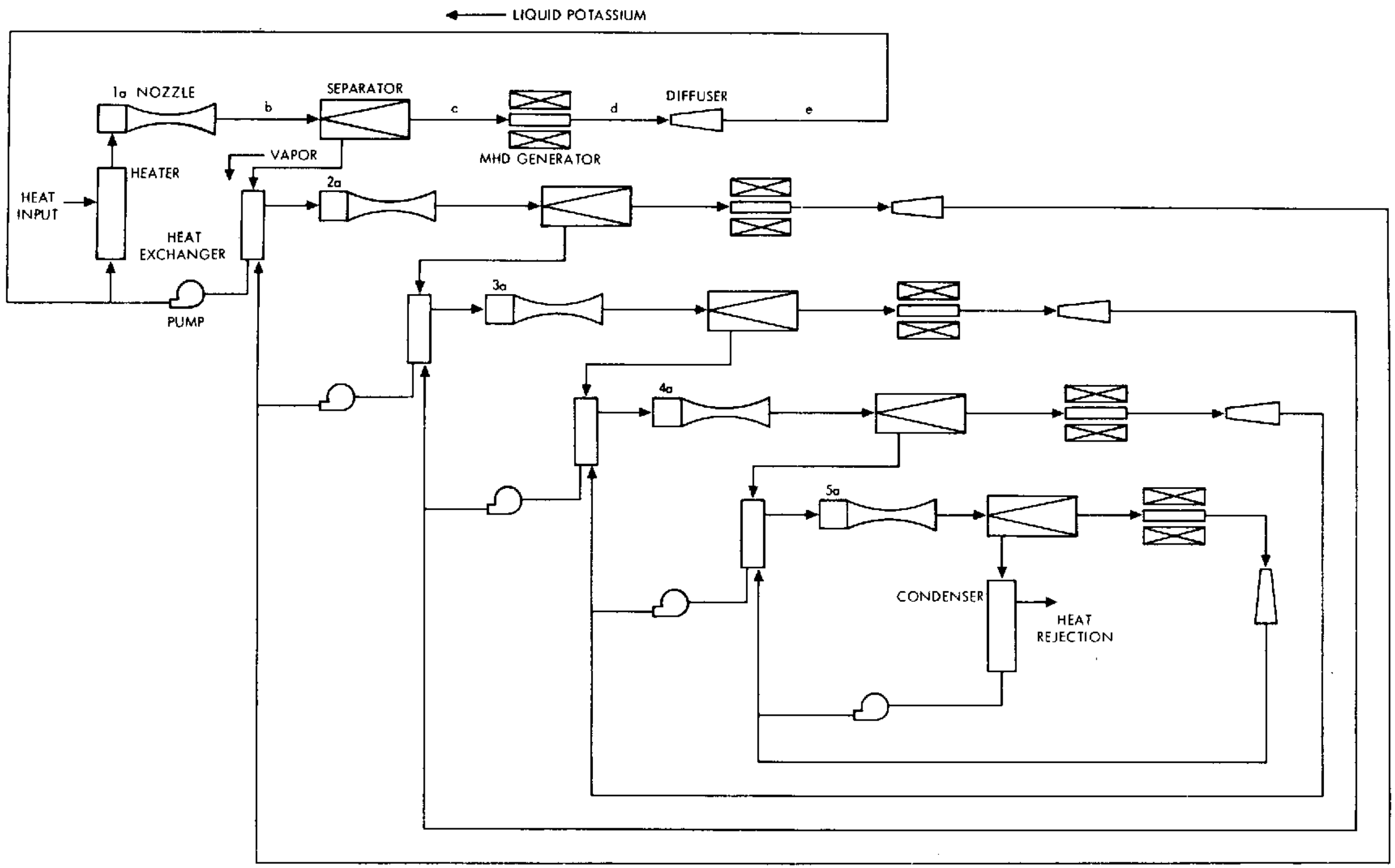

Fig. C-6. Multistage single component separator cycle (5 stage potassium shown) low vapor quality (0.01-0.10) at the maximum cycle temperature. The flow is expanded in a nozzle to a pressure resulting in a higher velocity and higher quality. This two-phase stream impinges on a surface separator. The high velocity liquid flows through the MHD generator producing power and is returned to the first stage heater. The vapor flows to a regenerative heater in the second stage. The first stage condensate is pressurized by a pump and returned to the first stage heater. This process continues through several stages. Finally, in the last stage, the heat from the condensate is rejected.

C. COMPONENT PERFORMANCE

Testing of components of both LMMHD separator cycles has been quite extensive. The cesium-lithium separator cycle tests have been conducted primarily in the USA, using other test fluids. Components of the potassium separator cycle have been tested largely in the USSR and West Germany, in conjunction with their investigations of potassium injector cycles.

1. Nozzles

The most efficient two-phase nozzles have been those using two-component flow. Tests of a large (50-in. length) nozzle using N_2-H_2O and Freon-H_2O mixtures have given exit velocities which are 89% and 92% of the isentropic values (8). These values result in energy efficiencies of 79% and 85%, respectively. In addition to the high efficiencies, the test results have shown excellent agreement with theory. Figures C-7 and C-8 (from Ref. C-8) illustrate the excellent correlation between theory and tests for the two fluid combinations above. For the two-component nozzle, which would be the type of nozzle in the cesium-lithium LMMHD system, the design techniques to obtain high efficiency appear to be well in hand.

For the case of a single component-two phase nozzle the results to date have not been as promising. Design of this type of nozzle is complicated by the fact that the ratio of liquid to vapor is a continuously varying quantity in the nozzle. The analysis, to be accurate, must consider supersaturation effects in the vapor. To date the most efficient single component nozzle had an energy

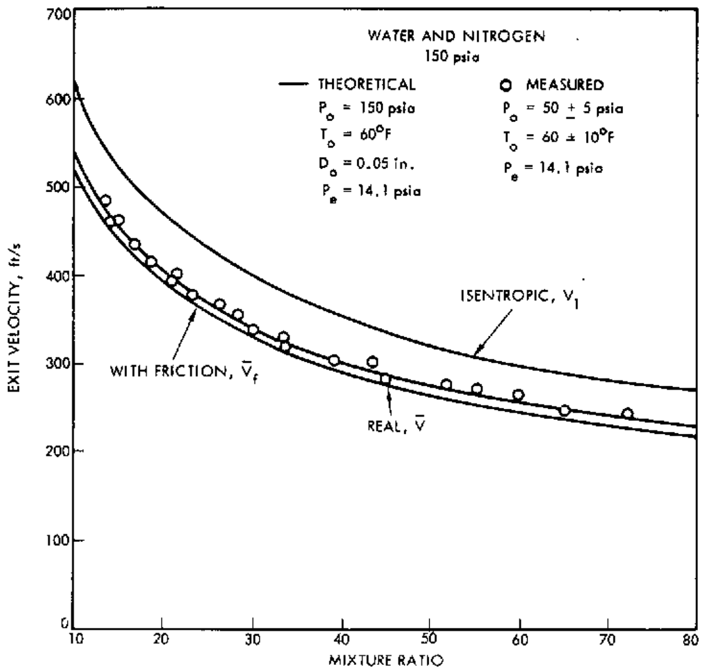

Fig. C-7. Comparison of theoretical and experimental exit velocities at 150-psia nozzle inlet pressure

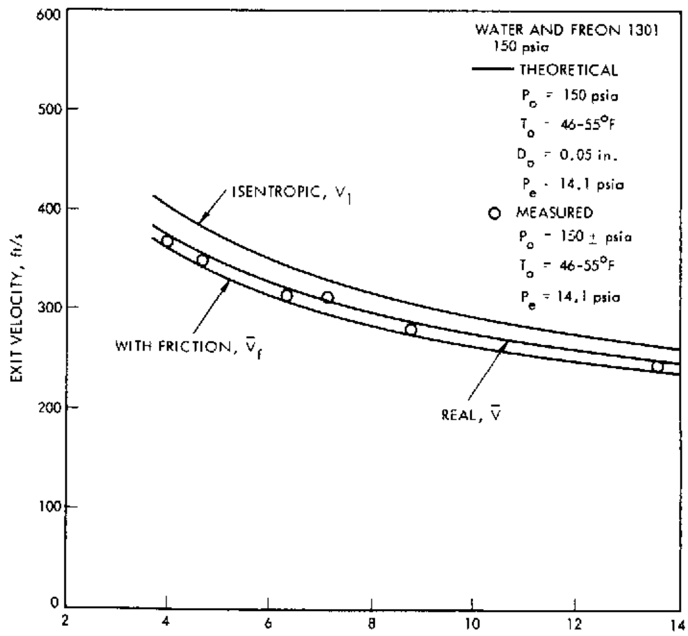

Fig. C-8. Comparison of theoretical and experimental exit velocities using Freon efficiency which was about 48% (Ref. C-9). Fairly good agreement both in trend and magnitude was obtained for theory and test data in this study. Part of the reason for lower efficiencies to date has probably been due to inadequate injector design.

2. Separator

The separator must provide nearly complete separation of the vapor and liquid phases at the nozzle exit without inducing large frictional losses in the liquid. Separators have been built and tested with nitrogen and water which provide 99% liquid flow at the outlet with an energy efficiency of 60% (Ref. C-10). The absolute value of the separator efficiency is low but is usable for a space power system. However, excellent agreement occurred between the test results and an analysis of the separator as shown in Fig. C-9. This same analysis when applied to the case of multiple stages predicts much higher efficiencies to occur due to lower values of vapor-liquid volume ratio and higher Reynolds numbers.

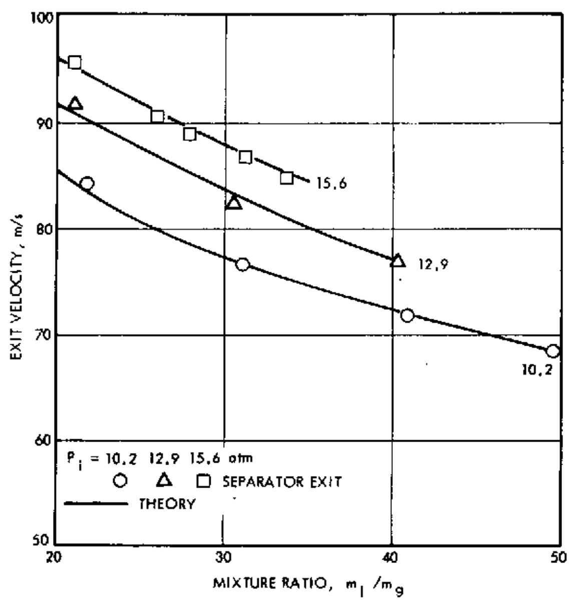

Fig. C-9. Comparison of measured and predicted velocity at exit of separator and upstream diffuser

Work has also been conducted on low loss, advanced separator concepts. Testing of impinging jet separators have shown that significant liquid concentration (> 3 to 1) is possible with very low velocity losses (Ref. C-31). More recent tests have shown that a sizable fraction of the component of kinetic energy normal to the surface separator is conserved. These tests may lead to the design of a surface separator of much steeper angle than previously tested with a concurrent reduction in frictional losses because of the lower surface area.

3. Generator

LMMHD generators have been tested by several groups using NaK and K as working fluids. Direct current generators have been tested in small sizes with net efficiencies of 75% with single phase liquid metal flow (Ref. C-11). The highest efficiency achieved for a two-phase dc MHD generator is 59% (Ref. C-7). The reason for the lower efficiencies obtained thus far are lower fluid electrical conductivity and/or vapor liquid slip problems.

For ac induction generators, the maximum efficiencies obtained thus far are on the order of 40-50%. Part of the reason for these lower values is the small scale of the generators tested. Another problem area is high end losses which can be encountered unless special stator winding techniques are used. More recently, a two-phase ac induction generator with 31 kW net power output has been tested at JPL. Continuing tests are oriented toward determining the maximum output and efficiency of this generator. Experiments thus far tend to validate a theory developed (Ref. C-12) which, when applied to large scale, lower velocity LMMHD generators such as would be used in a central station power system, gives efficiencies in the range of 80-85%.

Experiments in the USSR (Ref. C-13) and West Germany (Ref. C-14) have shown the feasibility of extracting power from a liquid metal stream at high temperatures (as contrasted to the low temperature experiments cited above). The generator stator and winding structure being installed for liquid metal testing in West Germany has been heated to temperatures in excess of 500°C with no electrical degradation.

4. Diffusers

In both separator systems being considered in this study, the diffuser is used for circulation of the larger liquid metal flow to achieve maximum efficiency. Other methods can be used, particularly in larger systems, but the diffuser remains the simplest and potentially most efficient method. The chief problem area in the diffuser is the possible occurrence of two-phase flow which usually results in supersonic flow requiring a convergent-divergent geometry for efficient pressure recovery.

For the cesium-lithium separator system, the amount of gaseous cesium entrained in the lithium leaving the separator is less than the equilibrium solubility at that temperature. Because of the large residence time (~ 0.1-0.2 sec) and high values of Reynolds number in large systems, it is expected that single-phase flow will occur at the diffuser inlet and an efficiency of 85% can be easily obtained.

The effects of void fraction on two-phase diffuser efficiency have been determined experimentally and are reproduced in Fig. C-10 (Ref. C-15). The efficiency was determined to be a slowly varying function of gas to liquid volume ratio. Even at a volume ratio of one (the highest which would be expected

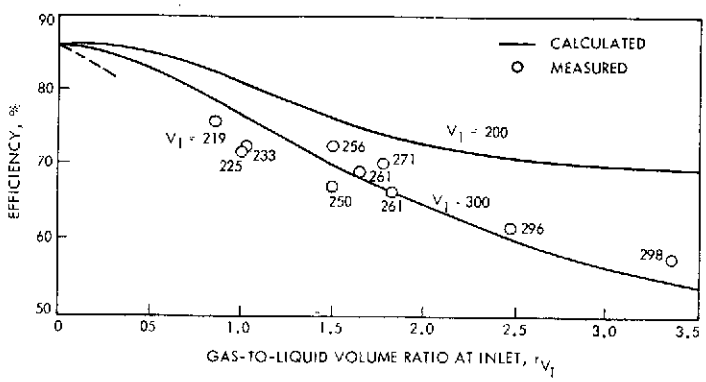

Fig. C-10. Comparison of measured annular diffuser efficiencies with values calculated for inlet normal shock plus 86% recovery of downstream stagnation pressure to occur), a diffuser efficiency of 75% was measured. This value would reduce the cycle efficiency by less than a half percentage point for the conditions of the topping cycle. The subject of two-phase supersonic flow has been studied extensively as applied to diffusers (Ref. C-15) and as basic research (Ref. C-16).

The results show that such a flow is analogous to single phase supersonic flow and that conventional normal shock and oblique shock relations can be used to design components. For example, Fig. C-11 (Ref. C-15) shows a comparison of the measured pressure profile with that calculated for a supersonic two-phase diffuser. The measured pressure rise and profile agree to within about 5% with the calculated values in the throat and divergent section.

5. Other Components

The other components for a LMMHD system are more conventional in nature, consisting of such items as gas-fired or shell-and-tube heat exchangers, centrifugal (or electromagnetic) pumps, high-temperature piping, and the required valving. Design relations and operating experience are extensive for other applications requiring the use of these components with liquid metals at

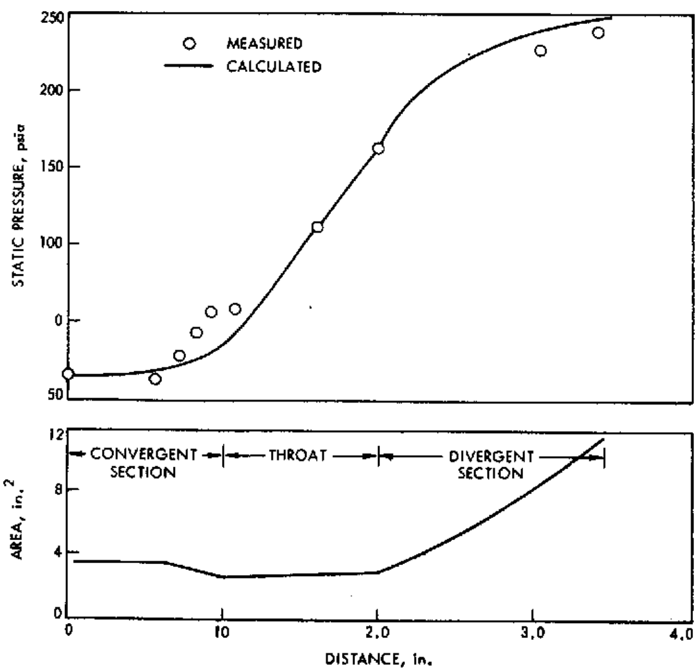

Fig. C-11. Comparison of calculated and measured static pressure profiles in annular diffuser temperatures as much as 700°F higher than this application (2500°F vs 1800°F) (e.g., Refs. C-17 through C-21). Even more work has been devoted to the subject of liquid metal corrosion.

Several materials have been identified as compatible with lithium and cesium or potassium at the temperatures of interest and higher (2650°F) (Refs. C-22 through C-26) and the effects of high velocity (Refs. C-27 and C-28) and protective coatings (Ref. C-29) have also been investigated. The material loss rates from protective Cb-1% Zr sheet and vapor deposited coatings in flowing lithium at 1800°F were negligible for a 100 hour period at a maximum velocity of 200 ft/s. The loss rates for Cb-1% Zr in flowing lithium at 2000°F were measured at a maximum of 7 μm for 500 hours at 160 ft/s. This corresponds to only 0.015 inches per year maximum for the operating conditions of a cessium-lithium topping cycle. In actuality the material loss and deposition rates would probably be much less than the above since the system would operate at 1800°F instead of 2000°F.

In addition, much of the technology, instrumentation and design techniques being developed for the Liquid Metal Fast Breeder Reactor Program are directly applicable to large LMMHD systems. The use of large liquid metal systems may seem to present a significant safety problem. However, radioactive liquid metal systems of a similar scale have been built and operated in commercial power facilities. Examples of these are the Enrico Fermi-I Installation, a fast sodium-cooled reactor rated at 70 MW electric power and the Hallam Installation, a thermal sodium-cooled reactor which provided 75 MW electric power. Decommissioning of the Hallam installation required the handling and disposal of in excess of 0.75×10^6 lb of radioactive sodium, comparable to the liquid metal inventory (non-radioactive) of the LMMHD topping plant having a 337 MW electrical output. In general, the areas of materials, reliability, and safety appear to be well in hand.

D. SYSTEM OPERATION

Startup and operation of lower temperature LMMHD conversion systems have been accomplished in the U.S.A. (Ref. C-29) and U.S.S.R. (Ref. C-13). Once the shakedown period was ended, both systems have proved easy to start up, control, and shut down. Other alkali metal systems of equal or greater complexity have been operated with very little difficulties at temperatures to 2500°F (Refs. C-17 through C-21). In one example, a gas-fired potassium turbine system was operated for over 11,000 hours (Ref. C-17). While this figure is small in comparison to the 20 to 30 year requirements of a central station power system, it is a result of the general design goals for a space power system (10,000-20,000 hr operation). Of greater significance is the high capacity factor attained. During a test of a three-stage turbine lasting 5000 hours, the use factor for the system was 66%, quite high for an experimental program which had programmed shutdowns to inspect the turbine.

E. LIQUID METAL MHD PROGRAM AT JPL

Liquid metal magnetohydrodynamic power generation was first proposed in JPL Technical Report 32-116, "A Two-Fluid Magnetohydrodynamic Cycle for Nuclear-Electric Power Conversion," July 30, 1961 by D. G. Elliott. The concept was patented by NASA in U.S. Patent No. 3,158,765, "Two-Fluid Magnetohydrodynamic System and Method for Thermal-Electric Power Conversion," November 24, 1964.

The first experiments were liquid acceleration tests with a two-phase nozzle using water and nitrogen in FY 1962. Freon-water tests verified the flash-vaporization process in 1963. Conical separators were also investigated in 1964, as well as two-phase diffusers.

The choice of cesium and lithium as the working fluids for high-temperature operation was made in 1963, and the required immiscibility of the two liquids was verified in tests to 1100°C. Static exposure tests of ceramics in lithium at 1100°C were begun in FY 1964. A computer program for two-phase nozzle analysis was developed. A blow-down facility for sodium-potassium liquid (NaK) was completed in 1964 and an output dc power of 11 KW was produced at 48% generator efficiency with a dc generator. The solubility of cesium in lithium was measured and cycle calculations of 300 KWe space power systems showed 6% cycle efficiency to be attainable. A 5 MW dc motor-generator (MG) set was purchased in 1964 for simulation of the nuclear reactor heat source in Cs-Li converter tests.

In FY 1965 the first closed-loop operation with a liquid metal was achieved in experiments with a NaK-nitrogen liquid metal converter without a generator. Exposure of ceramics to 1100°C lithium for 4000 hours was completed. A supersonic two-phase (water-nitrogen) tunnel was put in operation to study shock waves in two-phase flow. A 5 MW heat rejection system for Cs-Li converter experiments was designed.

Tests of ac induction generators were conducted in FY 1966, culminating in the generation of 1.0 KW of 700 Hz, three-phase power in a self-excited generator using compensating poles for suppression of end losses; this new generator concept was patented by NASA in U.S. Patent No. 3,422,291, "Magnetohydrodynamic Induction Machine," January 14, 1969.

A circulating lithium loop constructed of columbium-zirconium alloy was put into operation in 1966 for evaluating resistance of materials to high velocity lithium. A new laboratory building was constructed for the liquid metal MHD program and occupied in 1966.

In 1967 the ac generator tests in the NaK blow-down facility were completed. A lithium loop constructed of Haynes-25, a candidate low-cost material for Cs-Li converter experiments, was operated. A new test section in the columbium-zirconium loop was operated at a lithium velocity of 60 m/s for 500 hours. Mass transfer was extremely low and was found to agree with conventional relations for turbulent flow at lower velocities. Computer programs were written for design of a 1000°C Cs-Li converter and analyses of flight systems.

In 1968 a 30 kWe NaK-nitrogen converter was fabricated, and water-nitrogen tests were conducted. The heat transfer characteristics of a generator channel wall concept were measured at 1100°C. A building for the 5 MW MG set was constructed.

In 1969 new concepts for low-friction separators were tested with nitrogen and water. Electrical tests without liquid metal flow were conducted on a 30-kWe induction generator for the NaK-nitrogen converter. The electrical conductivity of cesium-lithium mixtures was measured under contract. The 5 MW MG set was installed.

In FY 1970 the first NaK flow tests were conducted with the NaK-nitrogen converter. A new loop for simultaneous flow of cesium and lithium at the full 150 m/s velocity of a conversion system was constructed. A study of liquid metal MHD systems for nuclear-electric propulsion was conducted under contract by the General Electric Company.

In 1971 the NaK-nitrogen converter generated electric power for the first time, and the cesium-lithium loop was started up. The 5 MW NaK-to-air heat rejection system for Cs-Li converter tests was installed.

In FY 1973 the NaK-nitrogen converter generated 30 kW of power.

A milestone chart summarizing the main events of the liquid metal MHD program is shown in Fig. C-12. The manpower for the liquid metal MHD project has been 3-4 engineers and 5-6 technicians since FY 1964. The average funding has been $600,000 per year, and the total cost through FY 1973 was $6.0 million.

Beginning in 1964, other laboratories in the U.S. and abroad have been conducting work on liquid metal MHD. Argonne National Laboratory and Atomics International have studied cycles for commercial power generation. Induction generator research has been conducted at M.I.T. and at University of Illinois. Commercial power cycles are being investigated at A.E.G., Berlin, and at the High Temperature Institute, Moscow. A liquid metal MHD space power system is being developed at the Krzhizhanovsky Power Institute in Moscow.

Thus, the liquid metal MHD program at JPL has not only furnished a potentially valuable space power generation method for NASA but has spearheaded a growing international effort on advanced commercial power generation using liquid metal MHD.

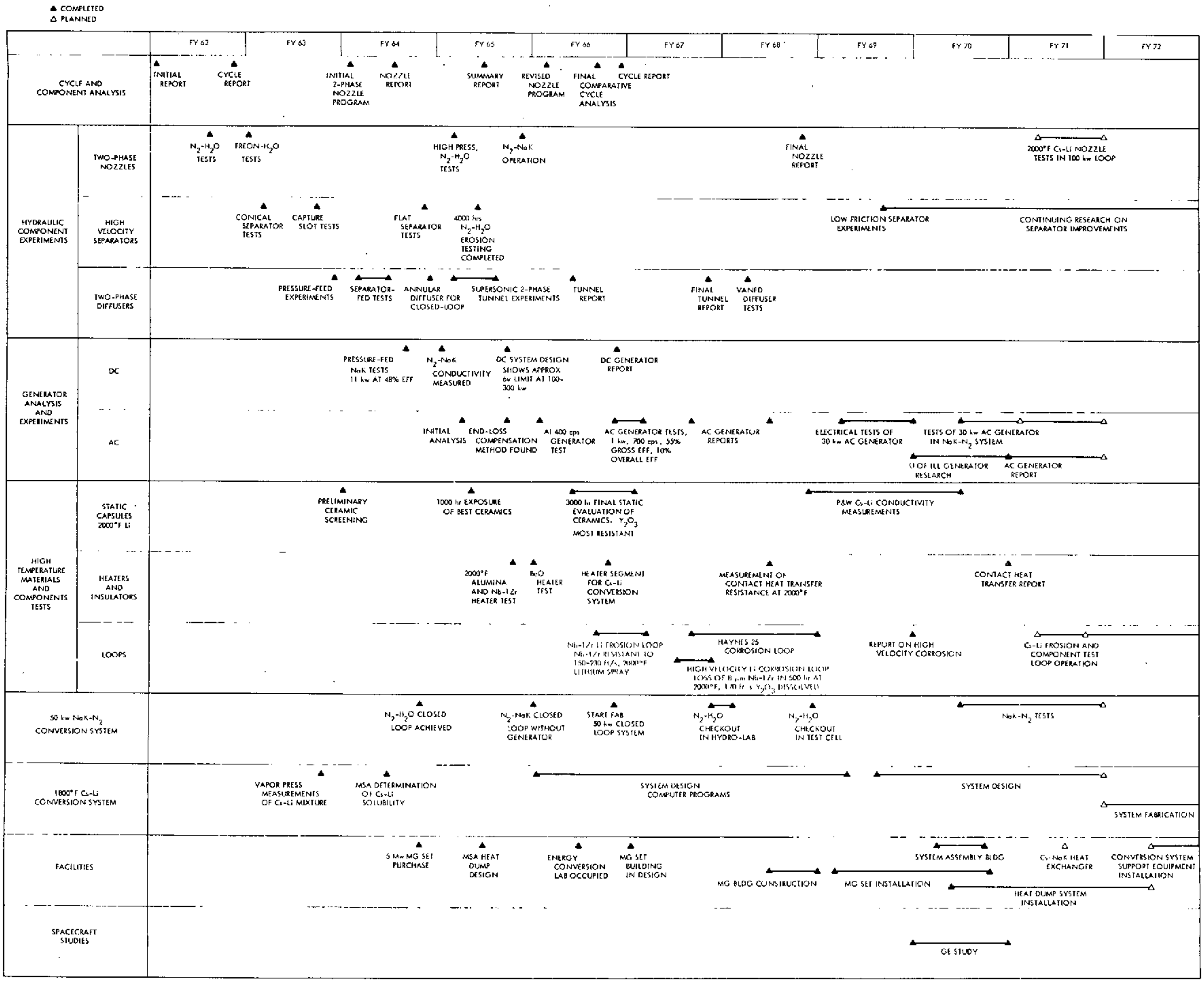

Fig. C-12. Liquid metal and program milestones

C-21

1200-59

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APPENDIX D

CYCLE ANALYSIS

A. INTRODUCTION

Two separator cycles were selected for more detailed analysis after the review of possible LMMHD cycles (Appendix C) was completed. These two cycles were (1) the potassium separator cycle and (2) the cesium-lithium separator cycle. The potassium cycle had the advantage of a less corrosive, less expensive working fluid, but its efficiency was known to be lower than the cesium-lithium cycle. The analyses determined that the potassium cycle efficiency was unacceptably low. Thus, the cesium-lithium system was selected for preliminary design (Appendix E). The following details the cycle analyses.

B. MULTISTAGE POTASSIUM SEPARATOR CYCLE ANALYSIS

1. Summary of Results

The initial direction taken on the LMMHD topping cycle study was consideration of a multi-stage potassium separator system. The cycle is shown schematically in Fig. C-6 of Appendix C. A previous study (Ref. C-2) had conclusively shown that a small, single-stage potassium separator system was much less efficient than a single-stage cesium-lithium system.

However, recent findings reported by Shpilrain (Ref. C-30) indicated that the inefficiencies may be overcome by staging and regenerative heating.

Shpilrain, in fact, reports a four-stage system with a thermodynamic efficiency of 19% and actual efficiency of 11-12% based on assumed component efficiencies. Independent calculations using Shpilrain's component efficiencies verified his reported cycle efficiencies. If these levels of efficiency could be attained, the potassium cycle would have an advantage over the cesium-lithium cycle because of the less corrosive nature of the potassium and the fact that it is less expensive than the lithium and cesium working fluids.

A detailed analysis was performed which calculated both nozzle and separator efficiencies. The nozzle inlet quality was varied from 0.01 to 0.10, values which yield higher thermodynamic efficiencies than the all-liquid inlet case of Shpilrain. The component efficiencies, however, were found to be lower than those assumed by Shpilrain. The results are summarized in Fig. D-1. Even with nine stages, the peak efficiency was only somewhat greater than 8%. If three stages were used, the maximum efficiency would be only about 6%. Because of the low efficiency, no further analysis of this cycle was conducted. Instead, efforts were concentrated on the cesium-lithium cycle.

2. Multistage Potassium Cycle Efficiency Analysis Using Calculated Nozzle and Separator Efficiencies

a. Nomenclature

Symbol		Definition	COMPUTER PROGRAM
C_p	=	specific heat of liquid potassium	CPA(N), CPB(N)
$L_{v_{na}}$	=	latent heat of vaporization, n^{th} nozzle inlet	LVA(N)
$L_{v_{nb}}$	=	latent heat of vaporization, n^{th} nozzle exit	LVB(N)
M_n	=	mass flow rate, n^{th} nozzle	M(N)
N	=	number of stages in cycle	S
p_{na}	=	n^{th} stage nozzle inlet pressure	PA(N)
p_{nb}	=	n^{th} stage nozzle exit pressure	PB(N)
p_0	=	maximum pressure in cycle	PA(1)
p_r	=	minimum pressure in cycle	PB(S)
P_{en}	=	electric power output of stage n	PE(N)
P_{eN}	=	net electrical power output	PEN
P_{eT}	=	total power output	PET
P_{pn}	=	required pumping power for stage n	PP(N)

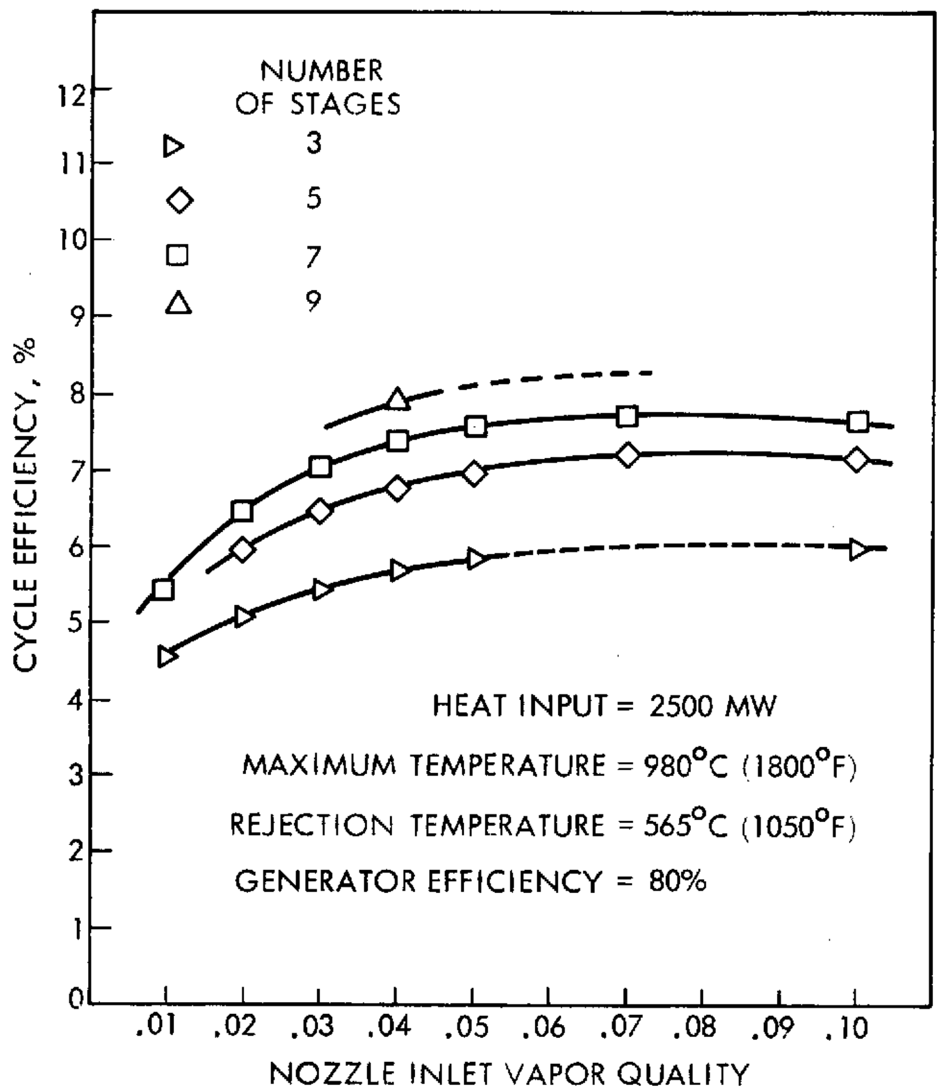


Fig. D-1. Efficiency of multistage potassium separator cycle vs nozzle inlet vapor quality

			COMPUTER PROGRAM
Q_n	=	heat input to stage n	Q(N)
Q_r	=	heat rejected from cycle	QR
T_{na}	=	fluid temperature, n^{th} nozzle inlet	TA(N)
T_{nb}	=	fluid temperature, n^{th} nozzle exit	TB(N)
T_{ne}	=	fluid temperature, end of n^{th} stage	
V_a	=	fluid velocity, nozzle inlets	VA
V_{nb}	=	fluid velocity, n^{th} nozzle exit	VB(N)
x_{na}	=	vapor quality, n^{th} nozzle inlet	XA(N)
x_{nb}	=	vapor quality, n^{th} nozzle exit	XB(N)
η_c	=	cycle efficiency	ETAC
η_D	=	efficiency of diffusers	ETAD(N)
η_{gn}	=	generator efficiency, n^{th} stage	ETAG(N)
η_{pn}	=	pump efficiency, n^{th} stage	ETAP(N)
η_{sn}	=	separator efficiency, n^{th} stage	ETAS(N)
ρ_ℓ	=	liquid potassium mass density	DLA(N), DLE(N), DL(N)

b. Analysis

An energy balance on mixing heater n gives:

$$Q_n + x_{(n-1)b}\dot{m}_{(n-1)}\left[L_{v_{(n-1)b}} + c_p T_{(n-1)b} + \bar{v}^2_{(n-1)b}/2gJ\right]$$

$$+ (1 - x_{nb})\,\dot{m}_n\, c_p\, T_{ne} + x_{nb}\,\dot{m}_n\left(c_p\, T_{nb} + \frac{p_{na} - p_{(n+1)a}}{\rho_\ell\, \eta_p\, J}\right)$$

$$= x_{(n-1)b}\,\dot{m}_{(n-1)}\;c_p\, T_{na} + \dot{m}_n(x_{na}\, L_{v_{na}} + c_p\, T_{na}) \qquad (1)$$

The exit temperature from stage n is equal to the total temperature at the nozzle exit less the useful energy terms:

$$T_{ne} = T_{nb} + \frac{\bar{V}_{nb}^2}{2gJc_p} - \left[\frac{(1 - x_{nb})(\eta_{gn})}{Jc_p}\right]\left[\eta_{sn} \frac{\bar{V}_{nb}^2}{2g} - \frac{p_{na} - p_{nb}}{\eta_D \rho_\ell} - \frac{V_a^2}{2g}\right] - \frac{(p_{na} - p_{nb})}{\rho_\ell J c_p} - \frac{V_a^2}{2gJc_p} \tag{2}$$

Substituting 2 into 1 and collecting terms gives

$$\Bigg[c_p T_{nb} + (1 - x_{nb}) \bar{V}_{nb}^2/2gJ - \frac{(1 - x_{nb})^2 \eta_{gn} \bar{V}_{nb}^2}{2gJ} \eta_{sn}$$

$$+ \frac{(1 - x_{nb})(p_{na} - p_{nb})}{\rho_\ell J}\left(\frac{(1 - x_{nb})\eta_{gn}}{\eta_D} - 1\right) + \frac{(1 - x_{nb}) V_a^2}{2gJ}\left((1 - x_{nb})\eta_{gn} - 1\right)$$

$$+ \frac{x_{nb}(p_{na} - p_{(n+1)a})}{\rho_\ell \eta_{pn} J} - x_{na} L_{v_{na}} - c_p T_{na}\Bigg] \dot{m}_n = - Q_n$$

$$+ \Bigg[x_{(n-1)b}\, c_p T_{na} - x_{(n-1)b} L_{v_{(n-1)b}} - x_{(n-1)b}\, c_p T_{(n-1)b}$$

$$- x_{(n-1)b} \frac{\bar{V}_{(n-1)b}^2}{2gJ}\Bigg] \dot{m}_{n-1} \tag{3}$$

For an equal pressure ratio per stage and N stages

$$p_{na} = \frac{p_0}{(p_0/p_r)^{(n-1)/N}} \tag{4a}$$

$$p_{nb} = \frac{p_0}{(p_0/p_r)^{n/N}} \tag{4b}$$

$$p_{(n+1)a} = \frac{p_0}{(p_0/p_r)^{n/N}} \tag{4c}$$

$$p_{(n-1)b} = \frac{p_0}{(p_0/p_r)^{n-1/N}} \tag{4d}$$

$$p_{(n-1)a} = \frac{p_0}{(p_0/p_r)^{n-2/N}} \tag{4e}$$

$$T_{na} = f_1(p_{na}) \tag{5a}$$

$$T_{nb} = f_1(p_{nb}) \tag{5b}$$

$$T_{(n-1)b} = f_1\left(p_{(n-1)b}\right) \tag{5c}$$

$$x_{na} = c_2 \tag{6a}$$

$$x_{(n-1)b} = f_2(c_2, N, p_{(n-1)a}) \tag{6b}$$

$$x_{nb} = f_2(c_2, N, p_{na}) \tag{6c}$$

$$V_{nb} = f_3(c_2, N, p_{na}) \tag{7a}$$

$$V_{(n-1)b} = f_3(c_2, N, p_{(n-1)a}) \tag{7b}$$

$$\eta_{sn} = f_4(f_2, f_3, \dot{m}_n, p_{nb}) \tag{8a}$$

$$\eta_{gn} = f_5(\dot{m}_n, \eta_{sn}, f_3) \tag{8b}$$

$$c_p = f_6(f_1) \tag{9a}$$

$$L_v = f_7(f_1) \tag{9b}$$

The electric power per stage is

$$P_{en} = \frac{\eta_{gn}(1 - x_{nb})\, \dot{m}_n}{J} \left(\eta_{sn} \frac{\bar{V}_{nb}^2}{2g} - \frac{p_{na} - p_{nb}}{\eta_D \rho_\ell} \right) \tag{10}$$

The total power is:

$$P_{eT} = \sum_1^N P_{en} \tag{11}$$

The heat rejected is

$$Q_r = \sum_1^N Q_n - P_{eT} + \sum_1^N P_{pn}/\eta_{pn} \tag{12}$$

where the pumping power is

$$P_{pn} = \frac{[p_{na} - p_{(n+1)a}]\, x_{nb}}{\rho_\ell J} \dot{m}_n \tag{13}$$

The net power is

$$P_{eN} = P_{eT} - \sum_1^N P_{pn}/\eta_{pn} \tag{14}$$

The cycle efficiency is

$$\eta_c = \frac{P_{eN}}{Q_r + P_{eN}} \tag{15}$$

The above equations were programmed in Fortran IV for a Univac 1108. The program listing follows:

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C     MULTISTAGE POTASSIUM SEPARATOR CYCLE PERFORMANCE ANALYSIS
C                     *** NOZZLE PROGRAM PROPERTIES ***
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C UNITS OF INPUT/OUTPUT QUANTITIES:    TEMPERATURES, DEGREES RANKINE
C                                      PRESSURES, PSIA
C                                      POWERS, MW
C                                      MASS FLOWS, LBM/SEC
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      REAL M,NS,LVA,LVB
      INTEGER S,CASE
      DIMENSION Q(9),XA(9),ETAP(9),ETAD(9),ETAG(9)
      DIMENSION PA(10),PB(9),TA(9),TB(9)
      DIMENSION XB(9),VB(9),LVA(9),LVB(9),DLA(10),DLB(9),DL(9)
      DIMENSION CPA(9),CPB(9)
      DIMENSION R1(9),R2(9),R3(9),R4(9),R5(9),R6(9),R7(9),R8(9),R9(9)
      DIMENSION ETAS(9),M(9)
      DIMENSION PE(9),PP(9)
      DIMENSION QNOZ(9),RENOZ(9),QPRIME(9),RE(9),CE(9)
    5 FORMAT ()
    7 FORMAT ('1CASE NUMBER',1X,I2////)
   10 FORMAT (' STAGE',9X,'ETAS',11X,'M',13X,'PE',13X,'PP'//)
   20 FORMAT (3H   ,I1,8X,F8.5,3(5X,E10.5))
   30 FORMAT (//' PET =',E10.5,' MW')
   40 FORMAT (' PEN =',E10.5,' MW')
   50 FORMAT (' QT =',E10.5,' MW')
   60 FORMAT (' QR =',E10.5,' MW')
   70 FORMAT (' ETAC =',F10.5)
   96 FORMAT (' ITERATIONS DID NOT CONVERGE.')
   97 FORMAT (' ETAS(',I1,') ASSIGNED VALUE OF 0.9.')
  100 G=32.17                @ FT/SEC**2
  110 J=778.2                @ FT-LB/BTU
  130 CASE=0
  140 CASE=CASE+1
  142 READ 5,S               @ NUMBER OF STAGES
  145 IF (S.EQ.0) GO TO 1000    @ ENDS PROGRAM RUN
  150 READ 5,(Q(N),N=1,S)       @ HEAT ADDITION AT EACH STAGE, MW
  156 DO 157 N=1,S              @ CHANGE FROM MW TO BTU/SEC
  157 Q(N)=Q(N)/1.055E-3
```

```
160 READ 5,(XA(N),N=1,S)     @ NOZZLE INLET QUALITIES
162 READ 5,(XB(N),N=1,S)     @ NOZZLE EXIT QUALITIES
165 READ 5,(ETAP(N),N=1,S)   @ PUMP EFFICIENCIES
170 READ 5,(ETAD(N),N=1,S)   @ DIFFUSER EFFICIENCIES
175 READ 5,(ETAG(N),N=1,S)   @ GENERATOR EFFICIENCIES
180 READ 5,VA                @ NOZZLE INLET VELOCITIES
185 READ 5,(VB(N),N=1,S)     @ NOZZLE EXIT VELOCITIES
186 READ 5,(PA(N),N=1,S)     @ NOZZLE INLET PRESSURES
187 READ 5,(PB(N),N=1,S)     @ NOZZLE EXIT PRESSURES
18  READ 5,(TA(N),N=1,S)     @ NOZZLE INLET TEMPERATURES
190 READ 5,(TB(N),N=1,S)     @ NOZZLE EXIT TEMPERATURES
195 READ 5,(LVA(N),N=1,S)    @ NOZZLE INLET LATENT HEATS OF VAPORIZATION
198 READ 5,(LVB(N),N=1,S)    @ NOZZLE EXIT LATENT HEATS OF VAPORIZATION
201 DO 205 N=1,S          @ CHANGE PSI TO PSF
202 PA(N)=PA(N)*144
205 PB(N)=PB(N)*144
210 PET=0.0                      @ TOTAL ELECTRICAL POWER INITIALIZED
215 PPT=0.0                      @ TOTAL POWER SUPPLIED TO PUMPS INITIALIZED
220 QT=0.0                       @ TOTAL HEAT ADDITION INITIALIZED
400 DO 420 N=1,S          @ CALCULATION OF THERMODYNAMIC PROPERTIES, ETC.
406 DLA(N)=12.6+0.5231*(3912-TA(N))**.5+2.635E-3*(3912-TA(N))
408 DLB(N)=12.6+0.5231*(3912-TB(N))**.5+2.635E-3*(3912-TB(N))
410 DL(N)=(DLA(N)+DLB(N))/2
415 CPA(N)=.227-.649E-4*TA(N)+.232E-7*TA(N)**2
420 CPB(N)=.227-.649E-4*TB(N)+.232E-7*TB(N)**2
430 DLA(S+1)=DLB(S)
435 PA(S+1)=PB(S)
440 DO 470 N=1,S          @ CALCULATION OF TERMS IN MASS FLOW EQUATION
445 R1(N)=CPB(N)*TB(N)+(1-XB(N))*VB(N)**2/(2*G*J)
450 R2(N)=(1-XB(N))**2*ETAG(N)*VB(N)**2/(2*G*J)
455 R3(N)=(1-XB(N))*(PA(N)-PB(N))*((1-XB(N))*ETAG(N)/ETAD(N)-1)/
   1(DL(N)*J)
460 R4(N)=(1-XB(N))*VA**2*((1-XB(N))*ETAG(N)-1)/(2*G*J)
462 H1=PA(N)/DLA(N)
464 H2=PA(N+1)/DLA(N+1)
466 R5(N)=XB(N)*(H1-H2)/(ETAP(N)*J)-XA(N)*LVA(N)-CPA(N)*TA(N)
470 R8(N)=R1(N)+R3(N)+R4(N)+R5(N)
475 DO 490 N=2,S
480 R6(N)=XB(N-1)*(CPA(N)*TA(N)-CPB(N-1)*TB(N-1)-LVB(N-1))
485 R7(N)=XB(N-1)*VB(N-1)**2/(2*G*J)
490 R9(N)=R6(N)-R7(N)
500 DO 795 N=1,S          @ BEGIN ITERATION FOR EACH STAGE
502 ITER=1                @ FIRST ITERATION
505 ETAS(N)=0.9           @ SEPARATOR EFFICIENCY INITIALIZED
507 NS=0.0                @ OLD VALUE OF ETAS INITIALIZED
510 DD=2.0                @ OLD INCREMENT OF ETAS INITIALIZED
512 IF (ITER.LE.10) GO TO 519
513 PRINT 7,CASE
514 PRINT 96
515 PRINT 97,N
516 ETAS(N)=0.9
519 IF (N.GT.1) GO TO 530
520 M(N)=Q(N)/(R2(N)*ETAS(N)-R8(N))          @ EFFECTIVELY SETS M(0)=0
```

```
525 GO TO 535
530 M(N)=(R9(N)*M(N-1)-Q(N))/(R8(N)-R2(N)*ETAS(N))
535 D=ETAS(N)-NS                 @ NEW INCREMENT OF ETAS
540 IF (ABS(D/ETAS(N)).LT.0.005) GO TO 775   @ COMPLETION OF ITERATION PCESS
545 IF (DD.LT.ABS(D)) GO TO 765        @ BRANCH IF DIVERGING
550 DD=ABS(D)                          @ OLD INCREMENT OF ETAS CHANGED
555 NS=ETAS(N)                         @ OLD VALUE OF ETAS CHANGED
556 ITER=ITER+1
557 IF (ITER.EQ.2) GO TO 560
558 RE(N)=REM*M(N)      @ NEW REYNOLDS NUMBER
559 GO TO 570
560 READ 5,QNOZ(N),RENOZ(N)
565 RE(N)=2.22*RENOZ(N)
568 REM=RE(N)/M(N)
570 CF(N)=.026/RE(N)**.2
575 QPRIME(N)=CF(N)*QNOZ(N)
585 IF (QPRIME(N).GT.0.02) GO TO 600
590 ETAS(N)=(.92-.0282*ALOG10(QPRIME(N)/.15))**2
595 GO TO 512              @ BRANCH BACK TO CALCULATION OF MASS FLOW
600 IF (QPRIME(N).GT.0.085) GO TO 615
605 ETAS(N)=(.86-.138*ALOG10(QPRIME(N)/.085))**2
610 GO TO 512
615 IF (QPRIME(N).GT.0.75) GO TO 630
620 ETAS(N)=(.84-.28*ALOG10(QPRIME(N)/.1))**2
625 GO TO 512
630 ETAS(N)=(.5-.298*ALOG10(QPRIME(N)/1.53))**2
635 GO TO 512
765 ETAS(N)=ETAS(N)-0.5*(ETAS(N)-NS)       @ FORCE CONVERGENCE OF ITERATION
770 GO TO 512
775 PE(N)=ETAG(N)*(1-XB(N))*M(N)*(ETAS(N)*VB(N)**2/(2*G)-
   1(PA(N)-PB(N))/(ETAD(N)*DL(N)))/J       @ POWER FROM STAGE (BTU/SEC)
780 PET=PET+PE(N)                          @ TOTAL POWER
785 PP(N)=XB(N)*M(N)*(PA(N)/DLA(N)-PA(N+1)/DLA(N+1))/J @ PUMP POWER FOR STAGE
790 PPT=PPT+PP(N)/ETAP(N)                  @ TOTAL PUMP POWER REQUIRED
795 QT=QT+Q(N)                             @ TOTAL HEAT ADDITION
800 PEN=PET-PPT                            @ NET POWER OUTPUT
805 QR=QT-PEN                              @ HEAT REJECTED
810 ETAC=PEN/QT                            @ CYCLE EFFICIENCY
811 DO 813 J=1,N        @ CHANGE BTU/SEC TO MW
812 PE(J)=PE(J)*1.055E-3
813 PP(J)=PP(J)*1.055E-3
814 PET=PET*1.055E-3
815 PEN=PEN*1.055E-3
816 QT=QT*1.055E-3
817 QR=QR*1.055E-3
819 PRINT 7,CASE        @ BEGIN PRINTOUT SEQUENCE
855 PRINT 10
860 DO 865 N=1,S
865 PRINT 20,N,ETAS(N),M(N),PE(N),PP(N)
870 PRINT 30,PET
875 PRINT 40,PEN
880 PRINT 50,QT
```

```
 885 PRINT 60,QR
 890 PRINT 70,ETAC
 900 GO TO 140            @ END CASE
1000 END
```

C. MULTISTAGE CESIUM-LITHIUM SEPARATOR CYCLE ANALYSIS

1. Summary of Results

A computer program to calculate cycle efficiencies was developed based on the analysis of Section B. The velocity at each stage was calculated for the given temperature and pressure ratio from a computer program for two-phase nozzles and was subsequently input to the cycle efficiency program. The separator efficiency was calculated, using parameters from the nozzle program. Values of 0.85, 0.70, and 0.80 were assumed for diffuser, pump, and MHD generator efficiencies, respectively.

As discussed in Appendix C, the aforementioned values appear to be conservative estimates and are representative of the values which would be attained for a large system. The single-phase diffuser and pump efficiencies have been routinely attained. The generator analysis of Ref. C-12 of Appendix C has predicted efficiencies as high as 85% for large systems. The maximum cycle efficiency is shown in Fig. D-2 as a function of the number of stages. Efficiencies greater than 14% are possible with three or more stages. Also note that the reduction in efficiency to two stages is not great, i.e., the efficiency is above 13.5%.

2. Multistage Cesium-Lithium Cycle Efficiency Analysis

a. Nomenclature

			Computer Program
n	=	number of stages	N
p_0	=	pressure at first stage nozzle inlet	PO
p_n	=	pressure at exit of last stage nozzle	PN
Δp	=	pressure drop through heat exchanger and nozzle inlet	DP
$\dot{m}_{\ell i}$	=	liquid flow rate in ith generator	MLG

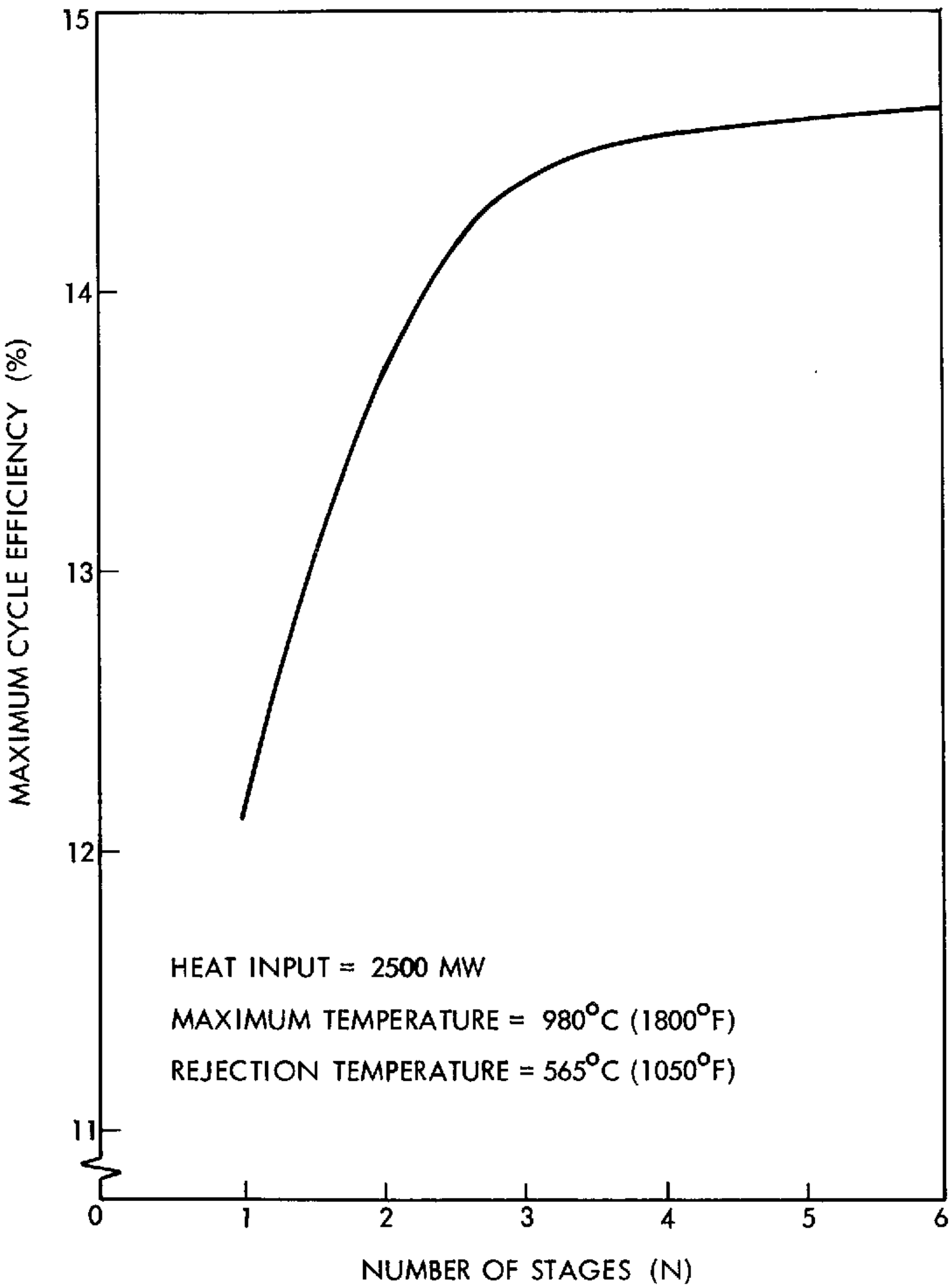


Fig. D-2. Maximum efficiency of multistage Cs-Li MHD topping cycle vs number of stages

			Computer Program
V_{gi}	=	liquid velocity in ith generator	VLG
P_i	=	power from ith generator	PG
η_{gi}	=	efficiency of ith generator	ETAG
η_{si}	=	efficiency of ith separator	ETAS
V_{ni}	=	velocity of liquid at exit of ith nozzle	VLN
η_D	=	diffuser efficiency	ETAD
$\rho_{\ell a}$	=	density of liquid lithium	DLB
$\dot{m}_{\ell n}$	=	liquid flow rate at exit of nth nozzle	MLN
$\dot{m}_{gn}$	=	vapor flow rate at exit of nth nozzle	MGN
η_p	=	pump efficiency	ETAP
$\rho_{\ell b}$	=	density of liquid cesium	DLA
Lv_b	=	latent heat of vaporization of cesium	LVA
β_n	=	fraction of lithium vapor in cesium flow	BETAN
T_n	=	temperature at exit of nth nozzle	TN
Cv_b	=	specific heat of cesium vapor	CPVA
T_0	=	temperature at inlet of 1st stage nozzle	TO
$C\ell_b$	=	specific heat of cesium liquid	CPLA
T_r	=	rejection temperature	TR
Lv_a	=	latent heat of vaporization of lithium	LVB

b. Analysis

From Fig. C-5 of Appendix C, the power extracted in generator "i" is

$$P_i = m_{\ell i}\eta_{gi}(V_{gi}^2 - 50^2)/2 \tag{1}$$

The generator velocity V_{gi} is related to the nozzle exit velocity by:

$$V_{gi} = \eta_{si}V_{ni} \tag{2}$$

Equation (1) becomes

$$P_i = \dot{m}_{\ell i}\eta_{gi}\left(\eta_{si}^2 V_{ni}^2 - 50^2 /2\right) \tag{3}$$

In the last stage or stages, sufficient dynamic head must remain to return lithium to the nozzle entrance. The power associated with this head is

$$P_r = \dot{m}_{\ell n}\left(\frac{p_0 - p_n + \Delta p}{\eta_D \rho_{\ell a}}\right) \tag{4}$$

Also to be provided from the gross electrical energy is that required to pressurize the cesium:

$$P_p = \dot{m}_{gn}\frac{\left(p_0 - p_n + \Delta p\right)}{\eta_p \rho_{\ell b}} \tag{5}$$

The total power is then given by

$$P_e = \left[\frac{1}{2}\sum_{1}^{n-1} \dot{m}_{\ell i}\eta_{gi}\left(\eta_{si}^{\ 2} V_{ni}^{\ 2} - 50^2\right)\right] + \dot{m}_{\ell n}\eta_{gn}\left(\frac{\eta_{sn}^{\ 2} V_{nn}^{\ 2}}{2} - \frac{p_0 - p_n + \Delta p}{\eta_D \rho_{\ell a}}\right) - \dot{m}_{gn}\frac{p_0 - p_n + \Delta p}{\eta_p \rho_{\ell b}} \tag{6}$$

or

$$P_e = \left[\frac{1}{2}\sum_{1}^{n} \dot{m}_{\ell i}\eta_{gi}\left(\eta_{si}^{\ 2} V_{ni}^{\ 2} - 50^2\right)\right] - \left(\frac{\dot{m}_{\ell n}\eta_{gn}}{\eta_D \rho_{\ell a}} + \frac{\dot{m}_{gn}}{\eta_p \rho_{\ell b}}\right)\left(p_0 - p_n\right) + \frac{50^2}{2}\dot{m}_{\ell n}\eta_{gn} \tag{7}$$

with the proper units

$$P_e = \frac{1}{47,500}\left[\sum_{1}^{n} \dot{m}_{\ell i}\eta_{gi}\left(\eta_{si}^{\ 2} V_{ni}^{\ 2} - 50^2\right) - 10,900\frac{m_{\ell n}\eta_{gn}}{\rho_{\ell a}}\left(p_0 - p_n + \Delta p\right) + 50^2\,\dot{m}_{\ell n}\eta_{gn}\right] - .390\frac{\dot{m}_{gn}\left(p_0 - p_n + 10\right)}{\rho_{\ell b}} \tag{8}$$

(for $\eta_D = .85$, $\eta_p = .50$)

The heat rejection is

$$Q_r = 1.055\ \dot{m}_{gn}\left[L_{v_b}\left(1 - \beta_n\right) + \beta_n\, 8780 + T_n - T_r\right) + C_{v_b}\left(1 - \beta_n\right)\left(T_n - T_r\right)\Big] - Q_\ell \qquad (9)$$

The heat absorbed by the subcooled cesium in passing through the regenerative heat exchanger is

$$Q_\ell = 1.055\ \dot{m}_{gn}\left[\beta_n + C_{\ell_b}\left(1 - \beta_n\right)\right]\left[T_0 - T_r\right] - .5\ P_p \qquad (10)$$

The cycle efficiency is therefore

$$\eta_c = \frac{P_e}{P_e + Q_r} \qquad (11)$$

These equations and a term which expresses the power which could be extracted from the cesium vapor were programmed in FORTRAN IV for a UNIVAC 1108 computer. The program listing follows:

```
          REAL LVA,LVB,MLN,MGN,MLG
          INTEGER CASE
          DIMENSION VLN(10),MLG(10),ETAS(10),ETAT(10),ETAA(10)
          DIMENSION PG(10),PA(10),PS(10),MGN(10),QNOZ(10),RENOZ(10)
          DIMENSION RE(10),CF(10),QPRIME(10)
       10 FORMAT ()
       15 FORMAT (2A6)
       20 FORMAT ('1CASE NUMBER ',I2,5X,'DATA SET ',2A6)
       30 FORMAT (' STAGE',9X,'ETAS',11X,'PG',13X,'PA',13X,'PS')
       40 FORMAT (3H    ,I1,8X,F8.5,3(5X,E10.5))
       50 FORMAT (' PE =',E10.5,' MW')
       60 FORMAT (' PAT =',E10.5,' MW')
       70 FORMAT (' QR =',E10.5,' MW')
       80 FORMAT (' QL =',E10.5,' MW')
       85 FORMAT (' QT =',E10.5,' MW')
       90 FORMAT (' ETAC =',E10.5)
       95 FORMAT (' ***** END OF PROGRAM RUN *****')
      101 CASE=0
      102 CASE=CASE+1
      104 READ 15,DATA
```

```
105 READ 10,N             @ NUMBER OF STAGES
107 IF (N.EQ.0) GO TO 900         @ ENDS PROGRAM RUN
110 READ 10,P0,T0         @ FIRST STAGE NOZZLE INLET PRESSURE, TEMPERATURE
115 READ 10,TR            @ REJECTION TEMPERATURE
120 READ 10,PN,TN         @ LAST STAGE NOZZLE EXIT PRESSURE, TEMPERATURE
130 READ 10,DP            @ REACTOR AND NOZZLE INLET PRESSURE DROP
140 READ 10,DLA,DLB,LVA,LVB,CPLA,CPVA,CPLB      @ FLUID PROPERTIES
150 READ 10,ETAP,ETAD,ETAG @ PUMP, DIFFUSER, GENERATOR EFFICIENCIES
160 READ 10,MLN           @ LAST STAGE NOZZLE EXIT LIQUID MASS FLOW RATE
165 READ 10,BETAN         @ LAST STAGE NOZZLE EXIT LI VAPOR MASS FRACTION
170 READ 10,(MGN(I),I=1,N) @ NOZZLE EXIT GAS FLOW RATES
180 READ 10,(MLG(I),I=1,N) @ GENERATOR LIQUID FLOW RATES
200 READ 10,(VLN(I),I=1,N) @ NOZZLE EXIT LIQUID VELOCITIES
210 READ 10,(ETAT(I),I=1,N)       @ TURBINE EFFICIENCIES
220 READ 10,(ETAA(I),I=1,N)       @ ALTERNATOR EFFICIENCIES
225 P0=P0*144.            @ CHANGE PSI TO PSF
226 PN=PN*144.
227 DP=DP*144.
230 DLA=DLA/32.174        @ CHANGE LBM/CU FT TO SLUG/CU FT
231 DLB=DLB/32.174
235 LVA=LVA*25030.        @ CHANGE BTU/LBM TO FT-LB/SLUG
236 LVB=LVB*25030.
240 CPLA=CPLA*25030.      @ CHANGE BTU/LBM-DEG TO FT-LB/SLUG-DEG
241 CPVA=CPVA*25030.
242 CPLB=CPLB*25030.
245 MLN=MLN/32.174        @ CHANGE LBM TO SLUG
250 DO 254 I=1,N
252 MGN(I)=MGN(I)/32.174
254 MLG(I)=MLG(I)/32.174
300 DO 385 I=1,N           @ CALCULATION OF SEPARATOR EFFICIENCIES
310 READ 10,QNOZ(I),RENOZ(I)      @ NOZZLE PROGRAM Q,RE
315 RE(I)=2.22*RENOZ(I)
320 CF(I)=.026/RE(I)**.2
325 QPRIME(I)=CF(I)*QNOZ(I)
330 IF (QPRIME(I).GT.0.02) GO TO 345
335 ETAS(I)=(.92-.0282*ALOG10(QPRIME(I)/.15))
340 GO TO 385
345 IF (QPRIME(I).GT.0.085) GO TO 360
350 ETAS(I)=(.86-.138*ALOG10(QPRIME(I)/.085))
355 GO TO 385
360 IF (QPRIME(I).GT.0.75) GO TO 375
365 ETAS(I)=(.84-.28*ALOG10(QPRIME(I)/.1))
370 GO TO 385
375 ETAS(I)=(.5-.298*ALOG10(QPRIME(I)/1.53))
385 CONTINUE
390 IF (N.EQ.1) GO TO 440  @ *** PERFORMANCE CALCULATIONS ***
400 NI=N-1
410 DO 430 I=1,NI
420 PG(I)=.5*MLG(I)*ETAG*((ETAS(I)*VLN(I))**2-65.**2)
430 PA(I)=.5*MGN(I)*ETAT(I)*ETAA(I)*(VLN(I)**2-50.**2)
440 PG(N)=MLG(N)*ETAG*(.5*(ETAS(N)*VLN(N))**2-(P0-PN+DP)/(ETAD*DLB))
450 PA(N)=MGN(N)*(.5*ETAT(N)*ETAA(N)*(VLN(N)**2-50.**2)-(P0-PN+DP)/
   1(ETAP*DLA))
```

```
460 DO 490 I=1,N
470 PS(I)=PG(I)+PA(I)         @ NET ELECTRICAL OUTPUT OF STAGE
480 PE=PE+PS(I)               @ NET ELECTRICAL OUTPUT OF CYCLE
490 PAT=PAT+PA(I)             @ TOTAL POWER FROM TURBO-ALTERNATORS
510 QL=MGN(N)*((BETAN+CPLA*(1.-BETAN))*(T0-TR)-(P0-PN+DP)/DLA)
520 QR=MGN(N)*((LVA+CPVA*(TN-TR))*(1.-BETAN)+BETAN*(CPLB*(TN-TR)+
   1LVB))-QL
525 QI=PE+QR                  @ THERMAL POWER INPUT
530 ETAC=PE/(PE+QR)           @ CYCLE EFFICIENCY
540 DO 560 I=1,N       @ CHANGE FT-LB/SEC TO MW
550 PG(I)=PG(I)*1.356E-6
555 PA(I)=PA(I)*1.356E-6
560 PS(I)=PS(I)*1.356E-6
565 PE=PE*1.356E-6
570 PAT=PAT*1.356E-6
575 QL=QL*1.356E-6
580 QR=QR*1.356E-6
590 QI=QI*1.356E-6
600 PRINT 20,CASE,DATA        @ BEGIN PRINTOUT SEQUENCE
610 PRINT 30
620 DO 630 I=1,N
630 PRINT 40,I,ETAS(I),PG(I),PA(I),PS(I)
640 PRINT 50,PE
650 PRINT 60,PAT
660 PRINT 70,QR
670 PRINT 80,QL
675 PRINT 85,QI
680 PRINT 90,ETAC
700 GO TO 102          @ END OF CASE
900 PRINT 95
1000 END
```

APPENDIX E

CESIUM-LITHIUM MHD TOPPING CYCLE DESIGN

A. INTRODUCTION

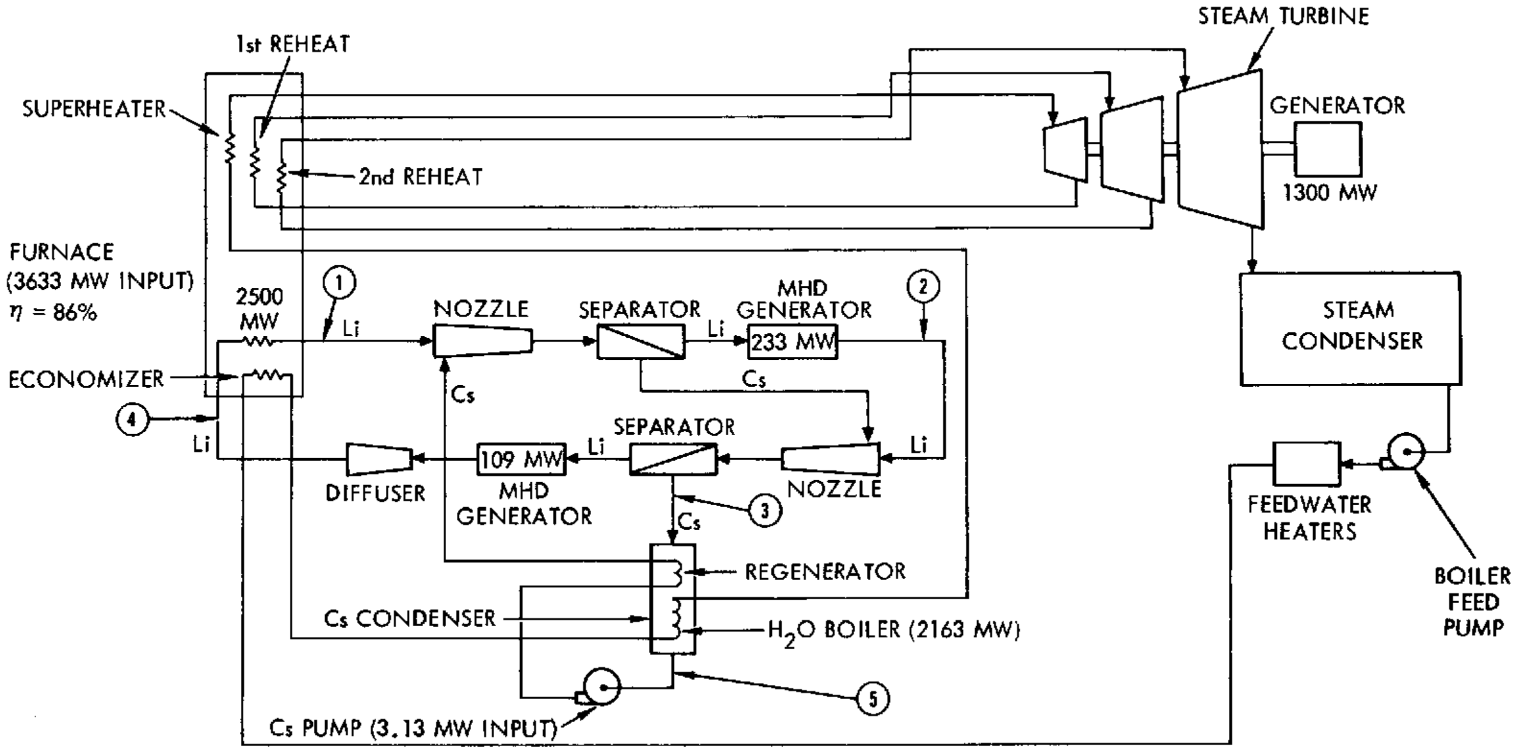
Analyses of cycle alternatives (Appendix C) and efficiency calculations (Appendix D) led to the selection of the cesium-lithium topping cycle for preliminary design. In this appendix, the selected cycle is described and cycle conditions are determined. Preliminary LMMHD system design is presented, including a system schematic design and layout, component description, materials and structural design, consideration of steam system interfaces and start-up, and auxiliary systems and controls. Finally, a cost estimate for the LMMHD system is provided, including specific capital costs projected to 1980.

B. DESCRIPTION OF CYCLE

The basic cycle chosen for final sizing and analysis is given in Fig. E-1. Lithium is heated in the furnace to a maximum temperature of 1808° F. The mass flow of 1×10^5 lb/s is mixed with liquid cesium at a pressure of 137 psia. The mixture is expanded in a nozzle to a pressure of 25.7 psia, resulting in an exit velocity of about 407 ft/s. The two-phase mixture is separated and the liquid lithium stream is passed through the MHD channel, generating 233 MW.

The lithium exiting at 100 ft/s is remixed with the cesium vapor and expanded to a pressure of 4.8 psia in the second stage nozzle, resulting in an exit velocity of about 400 ft/s. The lithium is separated from the cesium vapor and passes through the second MHD channel, generating 109 MW. The remaining dynamic head is used to increase the pressure to 152 psia to return the flow through the furnace to the first stage nozzle. The total temperature drop in the lithium is only about 24° F, so the heating in the furnace is nearly isothermal.

The cesium vapor separated from the lithium in the second stage flows through a regenerator, where the latent heat of lithium vapor in the cesium



LMMHD STATE POINTS

	°F	psia	lb/s	lb/s
	T	P	$\dot{m}_{Li}$	$\dot{m}_{Cs}$
1	1808	142	1×10^5	—
2	1792	25.7	1×10^5	—
3	1784	4.8	—	7.09×10^3
4	1785	152	1×10^5	—
5	1000	4.3	—	7.09×10^3

NOTE - STEAM CONDITIONS TYPICAL OF MODERN DOUBLE REHEAT CYCLE, 1050°F MAXIMUM TEMPERATURE.

Fig. E-1. Schematic diagram of Li-Cs liquid metal MHD - steam turbine binary cycle vapor and some of the cesium superheat is transferred to the cesium condensate. The cesium vapor then condenses on the primary boiler tubes, transforming the waste heat from the topping cycle into useful enthalpy of steam.

The cesium pump pressurizes the condensate to about 150 psia, returning it through the regenerative heat exchanger to the first stage nozzle, completing the cesium part of the cycle.

C. DETERMINATION OF CYCLE CONDITIONS

1. Maximum Temperature

The maximum temperature of a topping cycle is usually limited only because of materials or heat source considerations. In general, higher temperatures result in higher efficiencies due to the increase in fluid availability. In the case of the cesium-lithium LMMHD cycle, however, the efficiency is maximum at a temperature of only 1800-1900° F. The vapor pressure of lithium and the subsequent lithium vapor carryover and heat rejection increase rapidly above that temperature range and produce a decrease in efficiency. Other liquid metal combinations could be used for high efficiency at higher temperatures, but it was felt that the technology was not sufficiently well developed to consider their use.

The temperature chosen was 1800° F which also corresponds to about the maximum useful temperature for L-605 (Haynes-Stellite No. 25) alloy. This alloy has demonstrated corrosion resistance to liquid metals and furnace gases at that temperature. It can be operated without a protective atmosphere (as contrasted to the refractory metal alloys) and conventional welding and fabrication techniques can be used. In tests reported in Ref. C-29, this alloy was used to contain high velocity lithium at 1800° F by using a vapor-deposited internal coating of Cb-1Zr and by using a mechanical insert of Cb-1Zr sheet.

The 1800° F temperature is compatible with conventional coal- or oil-fired furnace practice. By using the furnace heat for the economizer and reheat sections of the steam turbine bottoming cycle and by having an air preheater, the furnace efficiency should be comparable to present units in the range of 85-90%. For the calculations, a value of 86% was used as being representative of current practice. High-temperature-gas or liquid-metal-cooled reactors could also be used with the LMMHD topping cycle. Several experimental reactors have been operated with gas temperatures sufficiently high for this application.

The combined efficiency of a furnace heated LMMHD-steam turbine plant is 45% versus an efficiency of 40% for a conventional furnace-steam turbine system. If a reactor were used, a combined efficiency of about 53% could be possible (section C-5).

2. Rejection Temperature

The rejection temperature chosen was 1050° F for the condensing cesium vapor. This value provides sufficient temperature difference to produce steam at modern conditions (1000-1010° F) with a compact heat exchanger geometry. Lower values, if used, would result in higher LMMHD efficiencies. However, for this study it was decided that the overriding factor should be providing steam conditions typical of a modern, steam turbine cycle. The value of condensing temperature means that chrome-moly steel or stainless steel can be used for the steam boiler tubing.

3. Power Level and Output Form

The basis for cycle calculations was a heat input of 2500 Mwt into the LMMHD heater. This value, when applied to a modern steam turbine cycle, would provide an output of about 1000 MWe, a common level. However, when the furnace inefficiency is taken into account, and the heat input directly to the steam cycle is considered, the total furnace heat requirement to provide 2500 MWt to the LMMHD heater is 3630 MWt (see Fig. E-1). This heat input would result in an output of 1300 MWe from the steam turbine plant and 337 MWe net from the LMMHD plant. When compared with a 3630 MWt input steam plant, the net increase due to the addition of the LMMHD plant is 180 MWe. This is an increase of 12% over a steam turbine system operating with the same thermal input (same fuel consumption). The steam turbine plant and furnace in the above example are approaching the largest sizes planned. However, two units could be used with no appreciable decrease in efficiency. For comparison with alternative systems (Appendix F) the design was normalized to provide an electrical output of 1000 MW.

The power from the MHD generators could be provided over a wide range of voltages or frequencies. For the purpose of estimating capacitor and generator costs, the voltage was assumed to be 4160 V at 60 Hz frequency. The voltage would remain constant with load decreases.

4. Thermodynamic State Points and Flow Balance

The more important state points are summarized in Fig. E-1. The total flow rate of lithium is about 1×10^5 lb/s and that of cesium is 7090 lb/s for a flow ratio of about 14 to 1. The lithium flow has a temperature change of only about 24° F and thus is nearly isothermal. The maximum lithium temperature is 1808° F and the maximum pressure is 152 psia. The condensing temperature and pressure for the cesium are 1050° F and 4.8 psia. Carryover of lithium vapor with the cesium was treated in the calculations (Appendix D); liquid carryover was not.

The presence of liquid lithium droplets in the cesium vapor has a small effect on cycle efficiency due to the presence of the regenerative heat exchanger. Each one percent of lithium carryover would result in lowering the cycle efficiency by about 0.25 percentage points. Carryover rates of only 1-2% or less are typical of experimental results to date. The separator and MHD generator components operate at essentially constant pressure and temperature so the state points are not repeated for those components.

The considerations that led to the choice of two stages rather than a greater number are discussed in the following subsection and in paragraph D.

5. Efficiency

The efficiency of the cesium-lithium MHD system was determined for the parameters given above by the analysis summarized in Appendix D. A three-stage cesium-lithium LMMHD system was selected for initial design consideration because of the rapid decrease in the efficiency added by each successive stage after the third. However, the large size of the third stage would make it difficult to achieve a reasonably compact plant layout without undue expense on the components and supporting structure. The long ducting which would therefore be required would necessitate a large inventory of liquid metal, and the liquid metal would spend a large proportion of its time in circulating through the ducting rather than in producing power. It was found that the structural material needed for such a system would be very large.

It was noted that reducing the system from three stages to two entailed a reduction in cycle efficiency on the order of 1 percentage point, while decreasing the capital outlay by roughly 50%. This reduction in efficiency was considered acceptable in view of the large savings in capital investment (see Appendix F, paragraph C). Moreover, the two-stage system lends itself to a compact layout, making effective use of the floor space required.

The two-stage LMMHD system chosen has an efficiency of 13.5% exclusive of furnace losses. Design of the furnace to achieve optimum efficiency is outside the scope of this program; however, use of a furnace efficiency of 86% means the net efficiency would be 11.6%. If a high-temperature reactor were used with a furnace efficiency of unity, the net efficiency would be 13.5% less any power consumption required by the reactor auxiliaries.

If all of the furnace heat was transferred to the liquid metal MHD heater, then the total plant efficiency would be

$$\eta_P = \eta_f \left[\eta_T + (1 - \eta_T)\,\eta_B\right]$$

where

η_P = total plant efficiency
η_f = furnace efficiency
η_T = LMMHD topping cycle efficiency
η_B = steam turbine bottoming cycle efficiency

For the calculated value of η_T = 0.135 and for typical values of η_f and η_B this becomes

$$\eta_P = 0.46$$

If 80% of the furnace heat goes into the LMMHD heater and 20% into the steam cycle, then:

$$\eta_P = 0.8\,\eta_f\left[\eta_T + (1 - \eta_T)\,\eta_B\right] + 0.2\,\eta_f\,\eta_B = 0.45$$

If the furnace efficiency were unity (as in a high-temperature reactor) and all the heat went into the LMMHD system, then a total efficiency of

$$\eta_P = 0.53$$

would be possible.

Due to the large size, much higher efficiencies were calculated for a topping cycle than for a space power system. For example, a single-stage space power system ($\sim$200 kWe) was calculated to have an efficiency of only 5.8% while a single-stage topping cycle had an efficiency of 12% for identical temperature and pressure conditions. The main reasons for the increase in efficiency at larger sizes are

1) The larger size permits the use of longer nozzles (for the same aspect ratio) which results in a lower pressure gradient and hence lower vapor-liquid slip and higher nozzle efficiency.
2) The larger size means that the liquid Reynolds number is larger and hence skin friction coefficients are smaller on the separator and generator duct surfaces.
3) The surface area/volume ratio in the generator duct becomes smaller as the size increases. This also reduces generator friction losses compared to the generator power output.

Increasing the number of stages produces a higher efficiency. This effect is primarily due to the lower liquid flow velocities and higher separator efficiencies in the upper stages (which are at higher pressure). The higher separator efficiencies result from the lower values of vapor to liquid volume ratio to be separated. Figure E-2 shows the effect of increasing the number

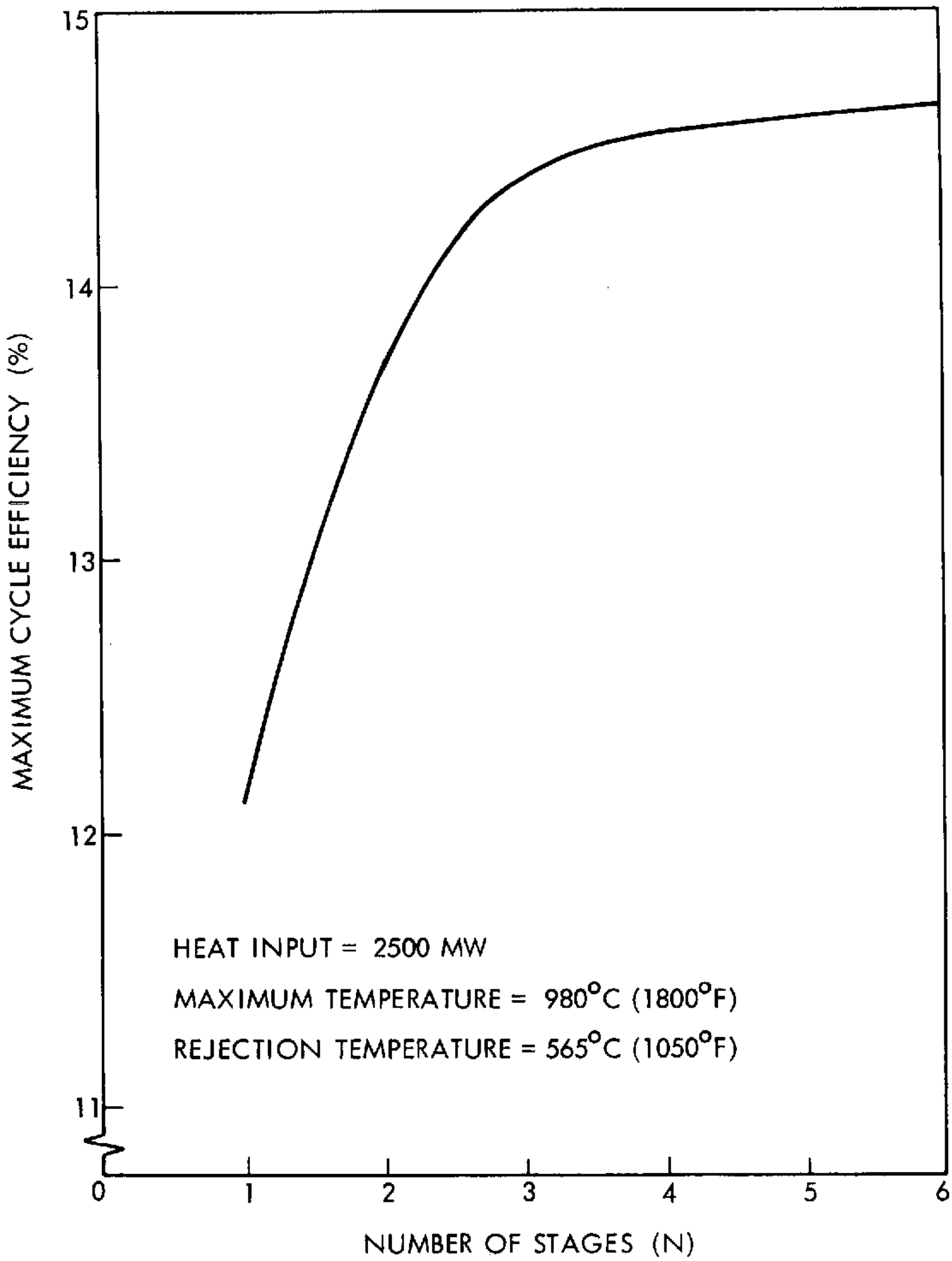


Fig. E-2. Maximum efficiency of multistage Cs-Li MHD topping cycle vs number of stages of stages at the optimum mass flow ratio. The efficiency increases from about 12% for a single stage to about 14.8% for seven stages. The initial increase from 12% to 13.5% for two stages is very large. Further increases are not as large. As discussed previously, the reduced rate of efficiency increase above two stages and the larger capital costs favored selection of two stages for the design example.

The optimum values of the ratio of lithium mass flow to cesium mass flow were found by varying the mass ratio from 5 to 25 and simultaneously varying the number of stages from 1 to 7. As shown in Fig. E-3, the peak efficiencies occur at a mass ratio of from 10 to 15. Although the peak efficiency point ($r_c \approx 14$) was selected for the design example, use of a lower mass ratio should produce a lower capital cost. This is due to a reduction in component size resulting from higher velocities in the nozzles and separators and smaller piping resulting from the lower liquid flow rates. For example, reduction from a mass ratio of 14 to 7 could reduce the capital cost by as much as 25% while decreasing the efficiency by about one percentage point. Thus, depending on the economic evaluation, further optimization with respect to mass flow ratio is possible and necessary for the lowest cost system.

D. PRELIMINARY DESIGN

The choice of the number of stages to be included in the design of an LMMHD topping cycle depends on many variables. The overriding consideration is that the cost of adding an extra stage must be weighed against the power output it adds to the system. Preliminary studies were conducted for systems having one, three, five, and seven stages in order to determine the dependence of the cycle efficiency on the number of stages.

The first operation in this study was the use of predetermined thermodynamic state points and other assumed conditions to determine the sizing and performance of the nozzles for each stage of each proposed system. This was accomplished with the aid of a computer program which employed the laws of two-phase, two-component flow to determine the flow conditions along each nozzle from the given inlet conditions.

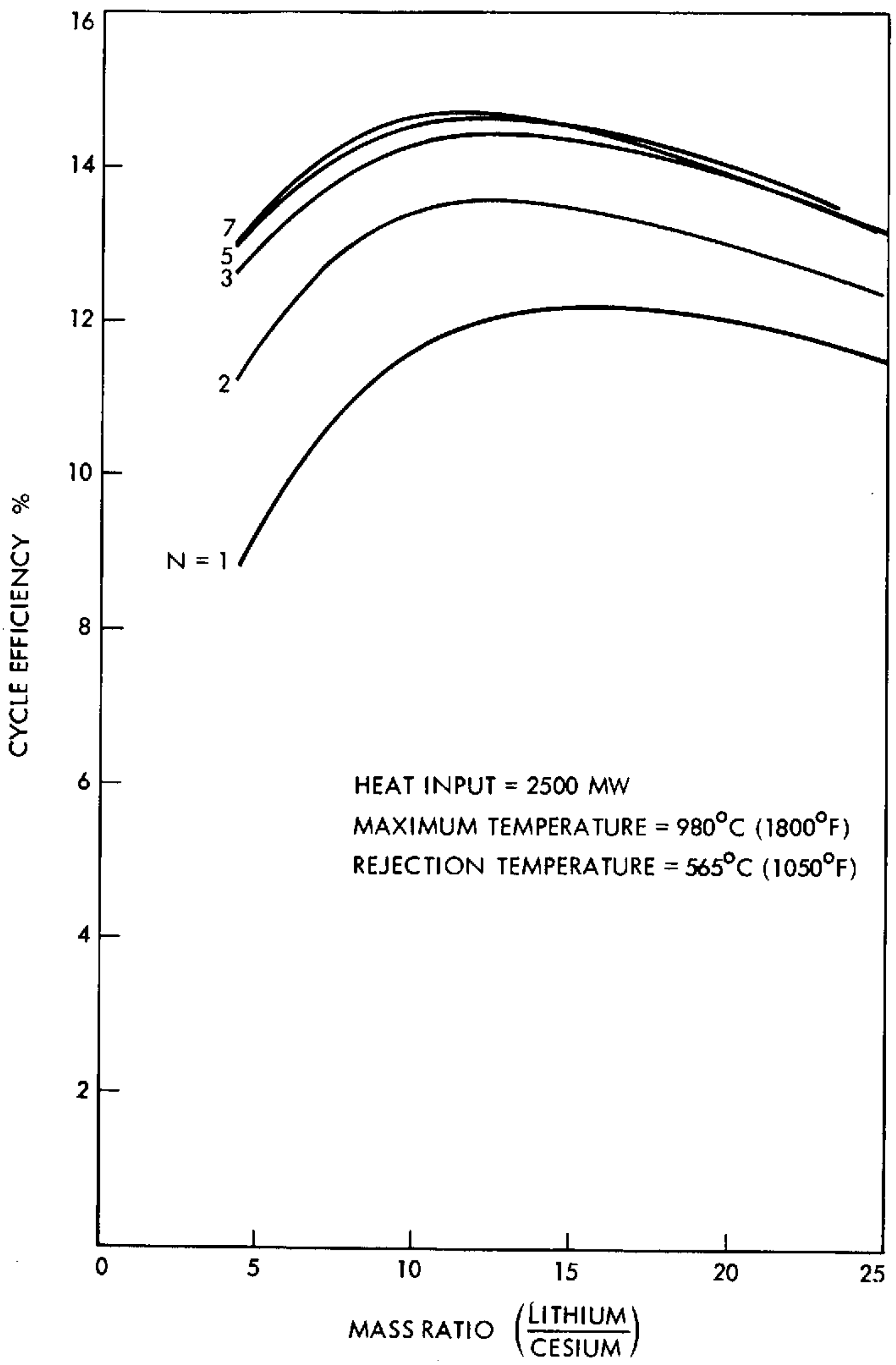


Fig. E-3. Efficiency of multistage cesium-lithium topping cycle vs mass ratio

The results of these calculations were analyzed by another computer program which determined the efficiency of each system, its heat input requirements, and other pertinent information. The resulting efficiencies were plotted against the number of stages in each system and the ratio of lithium mass flow to cesium mass flow. Examination of these graphs seemed to indicate that the optimum system would have three stages and would operate at a mass flow ratio of about 14, with a topping cycle efficiency of about 14.5%. This result was based on nozzles each having lengths of 1.00 ft and inlet velocities of 50 ft/s, and on the requirement for equal exit velocities for the nozzles in each given system.

A plant layout and a preliminary cost analysis of this system were performed. It was found that the large size of the third-stage components precluded the design of a reasonably compact plant layout. This necessitated an arrangement of long, large-diameter, liquid-metal ducting in the system. The large liquid-metal inventory needed to fill these lines, along with the structural material needed to build the third-stage components, raised the necessary capital investment to intolerable levels ($350-$400 per kW).

Changing from a three-stage system to one having two stages, the topping cycle efficiency is reduced by approximately 1 percentage point. However, we would expect the size of the two stages to be only slightly larger than the first two stages of the three-stage system, thus eliminating a large amount of liquid-metal ducting by allowing a more compact design. These considerations led to a complete analysis of the two-stage topping cycle presented here, and the expectations were borne out by the results.

1. Component Description

The final binary cycle design is represented in schematic form in Fig. E-1. Liquid lithium passes through the furnace at a flow rate of approximately 100, 000 lb/s and absorbs 2500 MWt, reaching a temperature of 1808° F at a pressure of about 142 psia. The lithium is injected into the first-stage nozzle where it is atomized by mixing with cesium vapor entering the nozzle at a flow rate of about 7090 lb/s. The average temperature of the flow upon mixing is

1800°F. The mixture accelerates to a velocity of about 400 ft/sec in the supersonic nozzle. It should be noted that a small fraction of the lithium becomes vaporized in the nozzle, raising the vapor flow rate. The amount of heat absorbed by lithium in vaporizing is significant and is utilized later in the topping cycle.

The two-phase mixture then enters a flat-plate separator which separates the mixture by impinging it on an inclined plate. Here, the liquid flow is diverted into the channel of the first-stage MHD generator, where it outputs 233 MW of electrical power.

The lithium is then injected into the second-stage nozzle where it is again mixed with the vapor extracted in the first-stage separator. The pressure at the inlet to the second-stage nozzle is about 25.7 psia, and the mixture temperature is about 1792° F. The mixture accelerates down this nozzle to roughly the same velocity as in the first-stage nozzle.

The mixture is again separated by impingement on an inclined plate in the second-stage separator. The liquid passes through the second-stage MHD generator where it gives up 109 MW of electrical power. It is then diffused to a velocity of approximately 20 ft/s and returned to the furnace. The lithium temperature at the furnace inlet is about 1785° F at a pressure of about 152 psi.

Meanwhile, the vapor leaving the second-stage separator passes through a regenerative heat exchanger, where it gives up about 269 MWt to the liquid cesium flow being pumped to the first-stage nozzle. This heat transfer is accomplished by the condensation of about half of the lithium vapor in the vapor-side flow. The vapor, with entrained droplets of lithium, then passes into the steam-generator/cesium condenser. Here the preheated feedwater for the steam cycle is boiled by passing through tubes exposed to the vapor flow. At the same time, the cesium vapor (and remaining lithium vapor) is condensed on the outside of the tubes.

The condensed liquid metal then enters a mechanical pump which sends the flow through the regenerator tubes so that the pressure and temperature reach the correct conditions for injection into the first-stage nozzle.

Characteristics of the major LMMHD converter components are summarized in Table E-1.

The steam turbine cycle was chosen to be representative of present-day designs. It is a double reheat system having a maximum temperature of 1050° F, and an electrical power output of about 1300 MW. No detailed design of the steam cycle was attempted, since the scope of this study was not intended to include such work.

It should be noted that the superheater and reheat sections of the steam cycle, along with the economizer for feedwater preheating, are included in the furnace housing with the lithium heater section, while the water boiler section is contained in a separate housing with the regenerator and cesium condenser.

A plant layout of the topping cycle is shown in Fig. E-4, which presents a side view and a top view of the plant. Structural ribbing is shown but the supporting structure is omitted for the sake of clarity. With this background, it is now advantageous to discuss the major components individually.

a. Furnace

The furnace is an oil- or coal-fired unit producing 3630 MWt. Its basic design is similar to that of conventional steam power plant furnaces and entails no new technological developments. Along with a lithium heater section, the furnace includes the steam superheater for the bottom steam cycle, the two reheat loops for the steam cycle, and a conventional economizer.

It should be noted that the major difference between this furnace and those usually employed in steam power plants is the replacement of the water walls at 1200°R with the lithium heater surface at 2300°R. Consequently, the lithium furnace will have higher bulk temperatures than a boiler and may also be larger in size. Another difference is that the liquid lithium undergoes a relatively small temperature rise in the furnace, resulting in smaller thermal stresses in the tubing as compared with conventional steam plant boiler-superheater units. Because only liquid lithium flows in the tubes (no vapor), hot spots are not to be expected.

Table E-1. Summary of characteristics of LMMHD converter components

1) First-stage nozzle
   - a) Length - 50 ft.
   - b) Exit area - 100 ft^2
   - c) Exit velocity - 407 ft/s
   - d) Exit temperature - 2252°R

2) First-stage separator
   - a) Surface area - 200 ft^2
   - b) Inclination angle - 30°
   - c) Efficiency - 0.905
   - d) Exit velocity - 387 ft/s

3) First-stage generator
   - a) Inlet aspect ratio (width/height ratio) 10.8
   - b) Length - 26 ft
   - c) Height - 92 ft
   - d) Width - 10 ft
   - e) Power output - 233 MW

4) Second-stage nozzle
   - a) Length - 75 ft
   - b) Exit area - 517.7 ft^2
   - c) Exit velocity - 399 ft/s
   - d) Exit temperature - 2244°R

5) Second-stage separator
   - a) Surface area - 1035 ft^2
   - b) Inclination angle - 30°
   - c) Efficiency - 0.742
   - d) Exit velocity - 344

6) Second-stage generator
   - a) Aspect ratio (width/height ratio) 50
   - b) Length - 21 ft
   - c) Height - 46 ft
   - d) Width - 22.8 ft
   - e) Power output - 109 MW

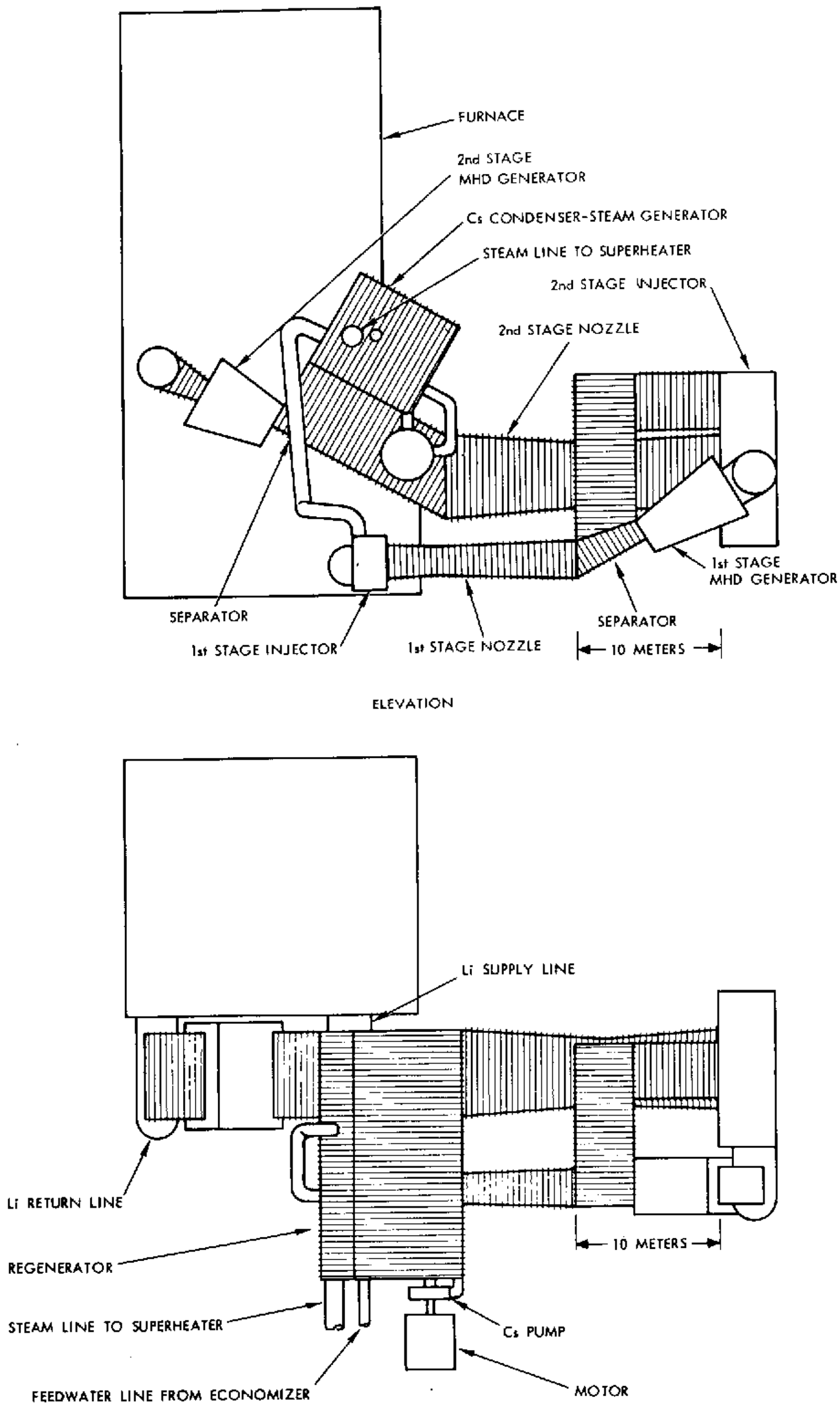


Fig. E-4. Schematic design of Cs-Li LMMHD - topping plant, 338 MWe output, 13.5% efficiency

From the work of Gorzegno, et al. (Ref. E-1), the average heat flux to the liquid metal in the heater section of the furnace is on the order of 60, 000 BTU/hr ft^{-2}. Computations show that tubing of Haynes-25 allow having an outside diameter of 1 in. and a wall thickness of 1/8 in. is satisfactory for use in the heater section, as it can provide adequate resistance to liquid-side erosion and to thermal stresses, while exhibiting good working properties for fabrication. The total length of tubing required under these circumstances is approximately 543, 300 ft.

The possibility of tube rupture in the boiler can be minimized by proper design for thermal stress. A tube rupture if it did occur could be tolerated with minimal damage to the furnace by a quick dump of the LMMHD circuits. Previous experience with a massive potassium leak at 1600° F in a gas-fired furnace has shown no catastrophic reactions to occur. If it was desired to minimize the liquid inventory which could be involved in such a rupture a two-loop system could be used at a slightly greater expense.

If the liquid side mass transfer is too large with the Haynes-25 material, thin wall Cb-1Zr tubes can be provided to mask the H-25 from the bulk flow velocity. As discussed previously this technique was shown to be successful in tests with 1800° F high velocity lithium in a Haynes-25 test system.

It is recognized that the furnace design will be a challanging task. Fireside corrosion with stainless steel has apparently been accelerated when wall or tube temperatures have been increased in the presence of normal sulfur-bearing fuels. Fireside-corrosion experimental data with Haynes-25 is needed.

b. Injectors

Each injector consists of a square array of 1/4-in. tubes, one foot in length, which leads from an injection manifold to the nozzle inlet. Liquid lithium passes through this system into the nozzle. The casing containing the tubing and the manifold serves as a plenum for the cesium, which is injected into the nozzle through the spaces between the lithium injector tubes. An example of such an injector is shown in Fig. E-5.

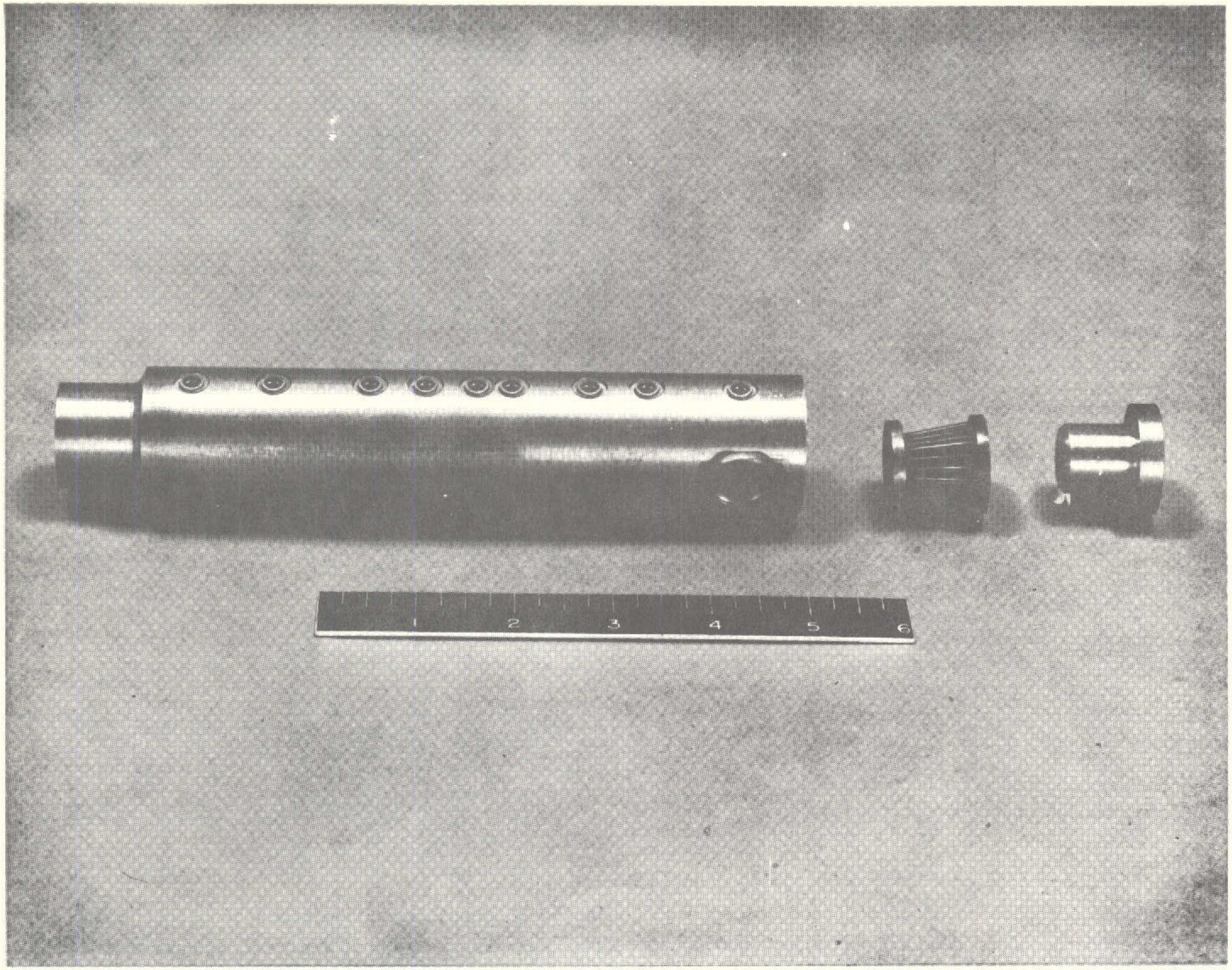


Fig. E-5. Small scale two-phase injector and nozzle

The pressure drops in the injectors comprise a significant loss in the system and, if the injection velocity is the same for each stage in a multistage system, this loss is the same for each stage also. Thus, as more stages are added to the system, this loss becomes a larger and larger percentage of the power produced by each stage. This accounts for the rapid decrease in the increment added to the cycle efficiency by the addition of extra stages as evidenced by the curves of Fig. E-3.

The net pressure drops calculated for the injectors in the two-stage cesium-lithium system are about 5 psi for each stage. These figures are based on an injection velocity of 100 ft/s for each liquid in each stage and 85% recovery of the exit velocity from each stage.

c. Nozzles

The nozzle design is closely related to the basic separator design since these components must combine to provide high velocity and low vapor quality flow for the MHD generators. Since the inclined-plane type of separator was chosen for the system, the nozzles were designed to have square cross sections.

Another reason for the choice of square nozzles is that such nozzles could be fabricated and assembled cheaply and rapidly, as described later, while circular nozzles would prove to be more costly. In addition, tests have shown that the mixing and acceleration characteristics of the two types of nozzles are essentially the same.

The sizing of each nozzle was performed with the aid of a computer program which utilized the laws of two-phase, two-component flow to find the flow properties by numerical methods from given inlet conditions and a specified lengthwise pressure distribution. For inlet velocities of 100 ft/sec in each stage for each fluid and for a linear lengthwise pressure distribution, the nozzle length which gave equal average exit velocities was chosen because of general arguments which indicated that the generator performance would be optimized by this condition. However, since the separator performance would be enhanced by better mixing in the low-pressure second stage nozzle, it is possible that a longer nozzle might be desired in the second stage than in the first. Any net improvement in system performance due to such a modification could prove to be significant.

Because of the material costs involved in these long nozzles, and in the interest of designing a reasonably compact system, it was decided to use nozzles which would be shorter than the 100 feet dictated by the requirement for equal exit velocities. The first-stage nozzle was shortened to 50 ft, and the second to 75 ft. The resulting drop in the exit velocities achieved was less than one percent for each nozzle, and this small change produced a very small change in the overall performance of the system.

d. Separators

As discussed previously, flat-plate separators were chosen for this system design study. In this type of separator, the high-velocity two-phase mixture entering from the nozzle impinges on a flat plate which is inclined at an angle to the flow direction. The liquid flow tends to form a layer which follows the plate to the separator exit, while the gaseous flow is forced into the area above the plate. The liquid then continues at high velocity into the MHD generator channel, and the gas is allowed to exit from the separator through a duct.

The important measures of the effectiveness of a separator design are the degree of separation of the fluid phases and the liquid velocity recovery through the separator. These properties depend on the velocity and vapor quality of the incoming two-phase flow.

The liquid velocity recovery is expressed by the separator efficiency, which is the ratio of the separator liquid exit kinetic energy to the inlet kinetic energy. The separator efficiency is a function of the inlet pressure and the Reynolds number.

Since the power output of the MHD generators depends directly on the flow velocity, the separator losses have a major effect on the cycle efficiency. Indeed, they constitute the largest single loss in the topping cycle. The calculated separator efficiencies in the cycle under study are 90.5% for the first-stage separator and 74.2% for the second.

The lower second stage separator efficiency is a necessary consequence of its operation at lower pressure. In a single stage system all the separation would be done at the lower pressure at an efficiency of about 74%. Thus, a very real gain is achieved by performing part of the separation (and power extraction) at a higher pressure.

e. MHD Generators

The topping cycle power is generated in multi-wavelength ac induction generators. Each generator has a set of copper windings in a removable stator assembly which is insulated from the hot channel by ceramic plates. The first-stage MHD generator is shown schematically in Fig. E-6. As noted, the first-stage generator is some 26 ft in length while the second-stage generator is 21 ft in length. The stator structures operate at a temperature of less than 200°F, making conventional motor winding materials and methods useable. Indeed, the flat configuration of the stators makes construction simpler than usual motor practice. Fabrication techniques currently being applied to large linear induction motors for high-speed train drives and conveyor belts are directly applicable.

The channel is simply ceramic plates protected by thin Cb-1Zr sheet which is attached to a Haynes-25 alloy backing structure. Depending on the results of a detailed design analysis, insulating vanes may be required at the inlet and exit of the channel. The stress in the channel wall is supported in compression against the stator structures. This is conventional practice in linear induction pumps where a similar requirement exists for a thin channel wall. The contract resistance to heat transfer of the ceramic plate, backed by ZrO_2 microspheres, has been shown to provide adequate thermal insulation for the stator structure (Ref. E-2). Electrical insulation is not required. Water cooling of the stator back side will provide the necessary heat removal to limit the stator temperature to 200°F. Thermal expansion compatibility of the structure requires further examination.

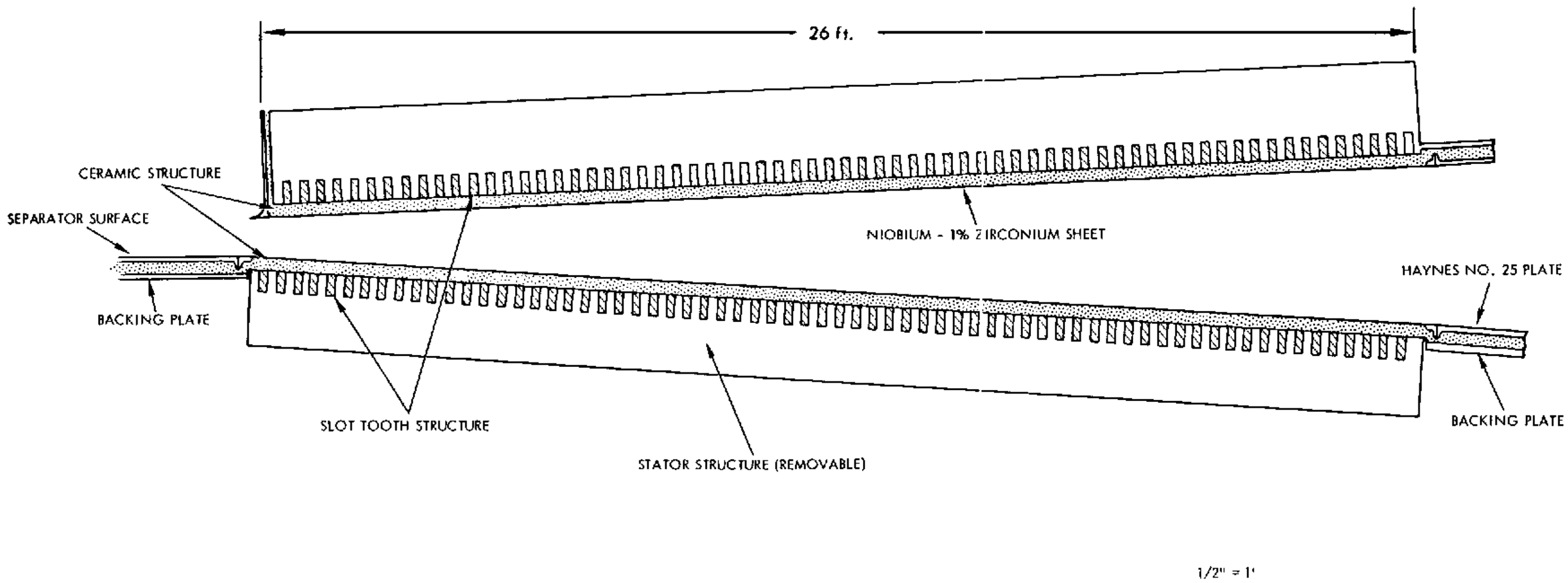


Fig. E-6. Schematic of first stage MHD generator longitudinal cross section

The magnetic field will be somewhat less than 1 Tesla in both generators, enabling construction of the stator with conventional materials. The analysis of Ref. E-3, when applied to the power level of the two MHD generators, predicts efficiencies of about 85%. Figure E-7, taken from that reference, shows this trend. A value of 80% was assumed in the calculations. If the 85% efficiency were attainable the cycle efficiency would improve from 13.5% to 14.3%. If 85% efficiency were attained in combination with the higher values of separator efficiency, the simple two-stage cycle would reach an efficiency of 17.2%.

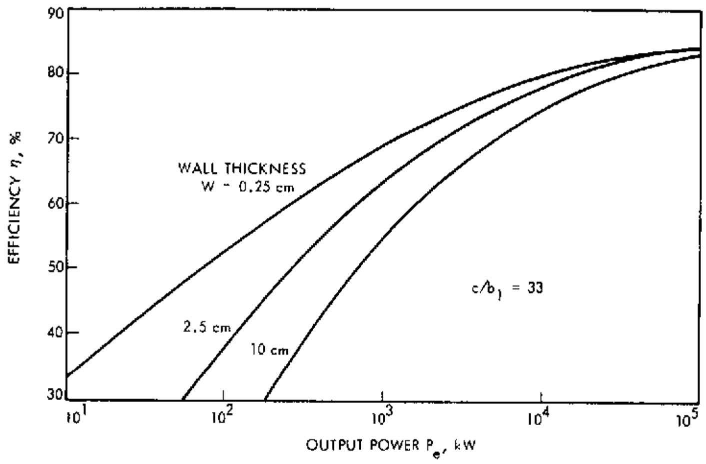


Fig. E-7. Effect of power level on LMMHD generator efficiency (from Ref. E-2)

f. Regenerative Heat Exchanger

The regenerative heat exchanger consists of an array of 6-in., Haynes-25 pipes within the Haynes-25 shell, which also contains the steam generator. A total of 100 pipes occupy about a 4-ft length of the shell. The total cesium pressure drop was only 0.35 psi for this configuration. Figure E-8 is a schematic drawing showing the arrangement of the regenerative heat exchanger and the steam generator in the Haynes-25 shell.

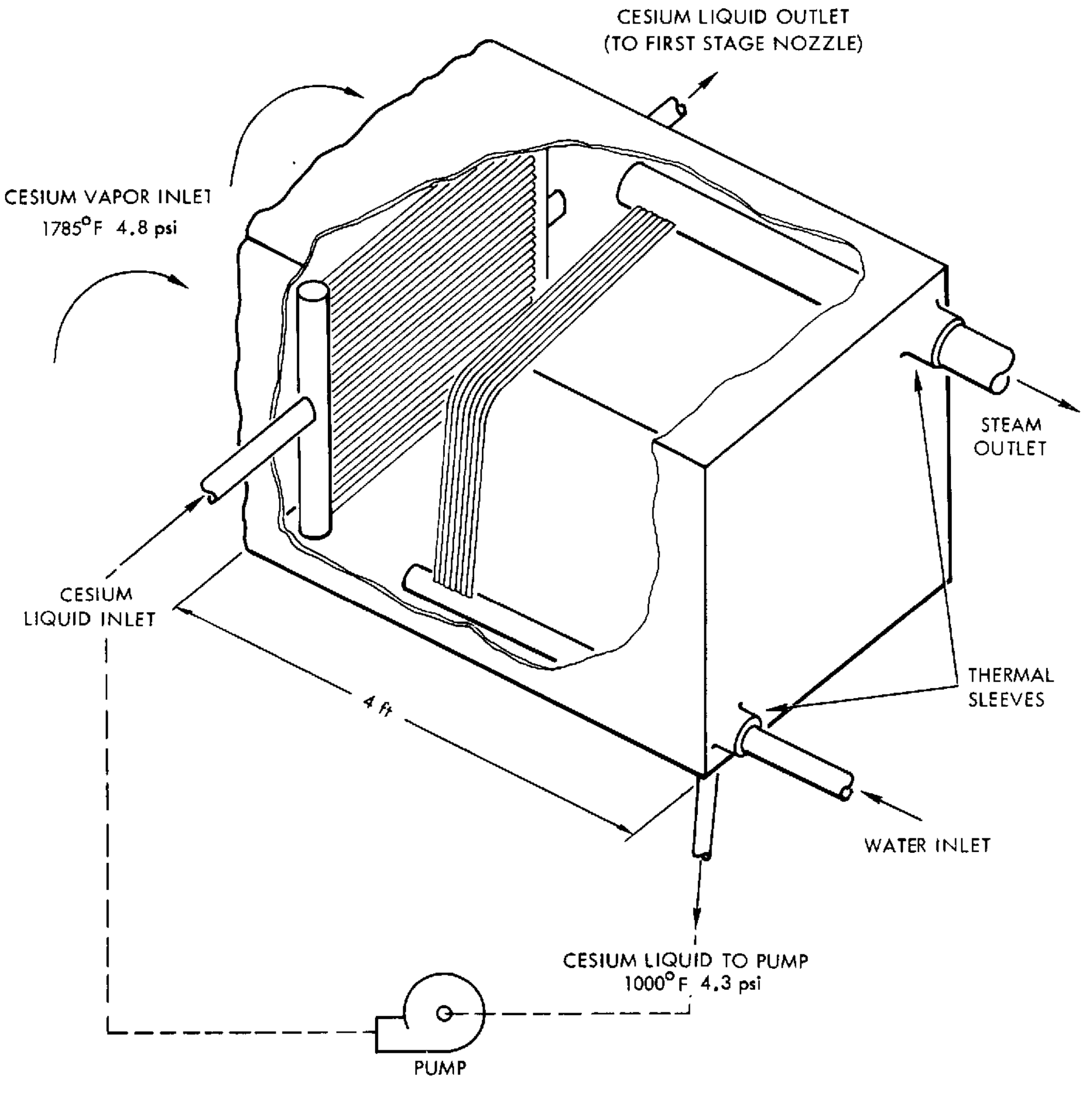


Fig. E-8. Schematic diagram of regenerative heat exchanger steam generator

g. Cesium Condenser-Steam Generator

The steam generator tubes occupy the rest of the volume of the Haynes-25 shell. Using the methods of Ref. E-4 a total of 1400 tubes, 40 ft long, will be required to transfer the heat input of 2163 MW to the steam. The steam tubing and headers can be constructed of either Series 300 stainless steel or chrome-moly steel and still be compatible with the condensing cesium at 1050°F. In the cost analysis, it was assumed that the cost of this tubing would be the same as in a conventional furnace-boiler. This is a conservative assumption since the required surface area and baffles in a furnace are much greater. The cost of the shell and regenerative heat-exchanger turbine was debited to the LMMHD cycle.

The cesium condenser/steam generator will have to be designed for fluids at extreme temperature ranges (cesium vapor at 1800°F, subcooled feedwater, and saturated steam). The design alternative considered here requires thermal sleeves for the pipe feedthrough and an interior baffle arrangement so that the walls "see" only the superheated cesium vapor.

2. Materials and Structural Preliminary Design

The high temperatures involved in the LMMHD topping cycle result in serious problems of structural design. In addition, the materials contacting the liquid metals must resist erosion and corrosion for the lifetime of the system. Among the few materials which have been found to be resistant to liquid lithium at high temperatures and flow rates are Haynes-25 alloy and Cb-1%Zr alloy. Of these, the latter is better in terms of corrosion resistance, but its high cost (about $60 per pound of sheet or plate) makes it undesirable as a basic structural material of the system.

Haynes-25, on the other hand, has an average cost of about $5.55 per pound for plate, which makes it acceptable as a structural material in spite of its somewhat lower corrosion resistance as compared with Cb-1%Zr. However, the acceptable stress levels for Haynes-25 at the high temperatures in the topping cycle are so low that it would not be economically feasible to build the nozzles and other components from this metal only. In fact, the fabrication scheme chosen as the basis for the cost analysis of the system employs Haynes-25 only for its resistance to corrosion by the liquid metals, and not as a main stress-bearing material.

Since many of the components of the system lend themselves to forms having square or rectangular, rathern than circular cross sections, it is advantageous to make use of fabrication techniques appropriate for the use of large flat plates or sheets of structural material such as in wind tunnel practice. The following preliminary design concept, which has been used previously, was devised to take advantage of this consideration, as well as to provide structural integrity at a minimum cost. It should be noted that the technique could also be used in the fabrication of the large-diameter circular ducts in the system.

A sample cutaway section of the finished structure is shown in Fig. E-9. Using chrome-molybdenum steel plate, 1-in. thickness, for most of the topping cycle components, and somewhat thicker for the high-pressure regions, an outer shell is fabricated. Before or after this assembly, studs are welded to the inside of the plate at intervals of approximately 2 ft, as represented in the figure. Then a surface of an appropriate forming material (such as plywood) is placed over the studs so that an air space of about 3 in. is formed between the outer metal shell and the inner wooden one.

Next, castable ZrO_2 is poured into the air space, filling it completely. Upon curing, this ceramic forms a thermal insulator for the outer shell. The forming mold is then removed and Haynes-25 plate is attached by welding to the exposed ends of the studs.

Thus, the Haynes-25 is primarily used to resist corrosion by the liquid metal while the studs and ceramic backing serve to transfer the pressure stresses to the outer steel shell. The insulating layer would allow a maximum outer shell temperature of less than 800° F, making 1/2 in. and 1-in. chrome-moly steel plate satisfactory for most of the system. The heat loss associated with this wall temperature gradient is less than 1 MWt for the whole system. This system must be supported by a constant force system to allow for thermal expansion. The support system has not been designed.

Haynes-25 appears sufficient to resist corrosion by the liquid metal in most parts of the topping cycle. The actual corrosion rates must be determined by extended duration tests. The inclined plates in the separators, however, are subjected to continual impact by high-temperature, high-velocity droplets of liquid lithium. Haynes-25 could not withstand this bombardment without severe erosion and mass transfer, However, sheets of mechanically attached Cb-1%Zr alloy have been used for mass transfer protection under similar conditions. Previous test data for 2000° F high velocity lithium flow, discussed in Appendix C, indicates a maximum mass transfer deposit build-up of 0.15 inches per year, quite insignificant for the dimensions of the separator surface and generator duct.

A proven scheme for installing such a plate is illustrated in Fig. E-10. A Cb-1%Zr sheet is squeezed between flanges on the nozzle and separator shells, as shown. The flanges are then welded to provide a leak-tight joint. The bent Cb-1%Zr sheet will be held down by the dynamic pressure of the impinging jet during operation. This scheme has been tested and has proven successful for short durations (Ref. C-29).

3. Interface with Steam System and Startup

The LMMHD topping cycle presented here interfaces with the steam turbine system in the primary evaporator section of the cycle. Economizer, superheater, and both reheat sections are located in the furnace. Startup of the steam turbine system will occur before startup of the LMMHD system. Furnace heat is transferred from the furnace to the cesium condenser-steam generator by evaporating cesium in the lithium heater.

The cesium evaporates at a temperature close to thé condensation temperature and flows to the steam generator where it condenses, transferring heat to the boiler. Cesium condensate is continually recycled to the furnace heating section by the cesium pump. When steady state operation of the steam turbine system is attained, 1800°F lithium is injected into the first-stage nozzle. Injection is continued until steady state operation is reached (~10-20 sec). Injection startup used with a smaller NaK-nitrogen LMMHD conversion system (Ref. C-10) produced steady-state operation in 1-2 sec.

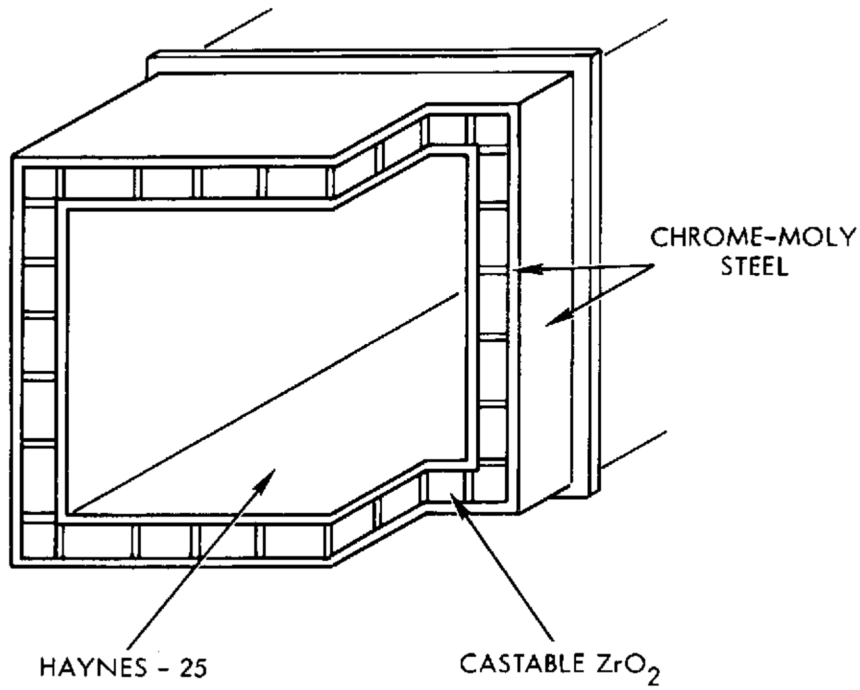


Fig. E-9. Duplex construction used for LMMHD topping cycle

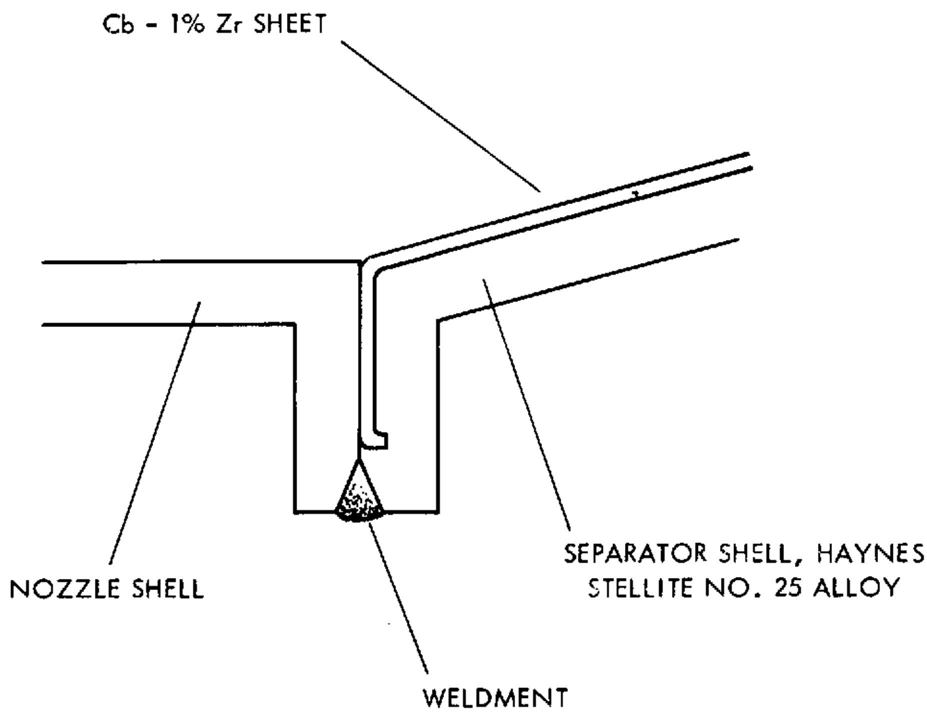


Fig. E-10. Method of securing columbium sheet for protection of high velocity of LMMHD topping cycle

Shutdown of the system must be sequenced so that stream flow is not lost before the heat input has been reduced to a low level. Part load operation will enable the heat load to be reduced while maintaining a constant temperature in the LMMHD system. The steam plant can be operated without the MHD generator so long as the MHD system is operable.

Although the primary application of the LMMHD system would be for base loading (efficiency is greatest at full load), it is possible for the system to operate under varying load conditions. By reducing the furnace heat, the maximum temperature of the liquid metal could be reduced, consequently reducing the liquid metal flow rate and the MHD power generation. The steam system would be throttled to match the liquid metal condition. The voltage can be maintained constant as the liquid metal velocity is reduced.

The control parameters on the furnace and steam turbine system, therefore, are identical to those for a conventional system. The control means for matching the LMMHD output to changing furnace heat rates is to vary the cesium inlet pressure and flow rates.

4. Auxiliary Systems and Controls

The auxiliary systems required for the LMMHD topping cycle will be quite similar to those required for the steam turbine system and, in general, such systems can be shared. Control air, vacuum systems, cover gas systems, auxiliary electrical, instrumentation and readout, and electronics are all conventional in nature. Control during startup is accomplished with conventional air-operated valving and gas pressure regulation equipment. During steady state operation, control is achieved by conventional furnace controls and controls on the steam turbine system.

E. COST ESTIMATE

A cost estimate for the LMMHD topping cycle was performed for the following assumptions:

1) The design life was to be 30 years.
2) The cost of the MHD generators is comparable to that of large electrical motors (on a unit power basis).
3) Haynes-25 corrosion characteristics are adequate for cesium vapor and low velocity lithium flow.
4) Cb-1Zr plate is used to protect high velocity regions (see paragraph C) from dissolution and/or extensive mass transfer.
5) The costs of components and materials are based on present-day manufacturers' quotations. Costs in 1980 were derived by assuming a five percent annual increase which was also applied to the alternative systems that were compared with the LMMHD/steam system.

With these constraints a summary of the cost estimate for the configuration of Fig. E-4 is given in Table E-2. It should be reiterated that the system has not yet been optimized with respect to cost. Operation at a lower mass ratio of lithium to cesium could result in a lower cost for the structure and liquid metal inventory while lowering the cycle efficiency by a small amount (i.e., about one percentage point).

The main cost uncertainty is the amount of Cb-1%Zr plate required to protect the internal surfaces from high-velocity lithium mass transfer. For the costs shown, only the separator and MHD generator surfaces were protected. If the other portions of the MHD circuit (cesium vapor and low-velocity lithium) had to be protected, the material costs would increase by about \$6.38 x 10^6. However, on the basis of published corrosion data and experience at JPL, this probably would not be necessary.

A possible reduction in cost could be achieved if it were possible to substitute a low-cost refractory material (such as silica) for the castable ZrO_2 backing structure. The use of more efficient separators would decrease the cost per added kW by enabling the production of more power. For example, if a separator efficiency of 95% could be attained in the first stage and 90% in the second stage, the cycle efficiency could be increased to 16.2% from the calculated value of 13.5% while the capital costs remained essentially constant.

Table E-2. Cost estimate summary for topping cycle for LMMHD-steam turbine binary power plant

Material Costs		($ x 10^6)	
Haynes-25 alloy plate	981,000 lb @ $ 5.55/lb	5.44	
Cb-1%Zr plate	7,600 lb @ 60.00/lb	.46	
ZrO_2 backing structure	2,704,000 lb @ 1.85/lb	5.00	
Cr-Moly steel plate	1,686,000 lb @ 1.00/lb	1.69	
Haynes-25 alloy tubing	543,300 ft @ 7.02/ft	3.81	
	74,300 lb @ 10.00/lb	.74	
	53,400 lb @ 10.00/lb	.53	
Structural steel (installed)	1,470,000 lb @ 1.00/lb	1.47	
Foundation (installed)	1,600 yd @ 50.00/yd	.10	
Insulation (installed)	41,300 ft^2 @ 1.30/ft^2	.05	
Component Costs			
MHD generators	342,000 kW @ 13.20/kW	4.53	
Cs pump		.50	
Capacitors	1,014,000 kvar @ 1.66/kvar	1.66	
Controls		.50	
Auxiliary Systems		1.00	
Dump and start tanks		4.87	
Total material and component costs		32.35	
Construction cost (25% of component costs, not including installed costs)		7.68	
Total Direct Costs		40.03	
Indirect costs (25% of direct costs)		10.01	
Total 1972 costs less liquid metals		50.04	
Liquid metal inventory 1972 costs			14.38
Liquid metal inventory 1980 costs			21.24
Total 1972 cost with liquid metals			64.46
Total 1980 cost without liquid metals			73.90
Total 1980 cost with liquid metals			95.14
Specific cost, 1980, without liquid metals (337 MWe)			219.0/kW
Specific cost, 1980, with liquid metal (337 MWe)			282.0/kW
Specific cost, 1980, liquid metal inventory			63.0/kW

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APPENDIX F

EVALUATION OF LIQUID METAL MHD AND COMPARISON WITH ALTERNATIVE SYSTEMS

A. INTRODUCTION

The LMMHD/steam binary system has been compared with alternative systems on the bases of costs and environmental impact. Technology status, reliability, maintainability and safety have been briefly considered.

Also included is a general topping cycle analysis which can be used to consider LMMHD/steam plant cost, performance and power trade-offs. A summary of the results of these evaluations is presented in the following sections.

B. EVALUATION SUMMARY

LMMHD topping plants with coal-fired, oil-fired and nuclear bottoming plants were evaluated in comparison with alternative systems. The following discussion summarizes the evaluation.

1. Coal-Fired LMMHD/Steam Plant

a. Costs

The coal-fired LMMHD/steam plant has superior or comparable costs when compared with all other systems considered. It has nominal 1980 generation costs 0.2 mills/kWh lower than the coal-fired steam plant, which has one of the lowest power generation costs of all plants considered. The coal-fired LMMHD/steam plant has generation costs which are comparable or lower than any other advanced power plant considered.

b. Environmental Pollution

The coal-fired LMMHD/steam plant has reduced thermal pollution due to its higher efficiency, than all conventional power plants. Advanced power plants with efficiencies higher than the LMMHD/steam plant will reduce the thermal pollution even more.

The coal-fired LMMHD/steam plant is predicted to produce less air pollution than the conventional coal-fired steam plant. However, because coal is used as the fuel, it will produce more air pollution than the other power plants considered, except the coal-fired plasma MHD/steam plant which is predicted to produce more NO_x.

c. Technology

The LMMHD/steam plant currently lags the alternative systems, except possibly plasma MHD, in technology development. It has received one to two orders of magnitude less funding than the other systems, however.

d. Reliability

Because the LMMHD/steam plant is a binary plant, it probably has less inherent reliability than a conventional steam plant.

The basic LMMHD simplicity predicts a reliable system, however. Operation at high temperature for long times with liquid metals are the primary factors which will reduce reliability.

e. Maintainability

Maintenance requirements for the LMMHD/steam system will depend, in part, upon erosion and deposition due to the circulating liquid metal and liquid metal handling requirements. Maintainability requirements for LMMHD are not yet known in detail.

f. Safety

The LMMHD/steam system is probably less safe than conventional systems and the plasma MHD/steam system due to the requirement for liquid metal handling. With the development of the liquid metal fast breeder reactor, liquid metal handling will become increasingly routine, however.

2. Oil-Fired LMMHD/Steam Plant

a. Costs

The oil-fired LMMHD/steam plant has nominal 1980 generation costs 0.1 mills/kWh lower than conventional oil-fired systems. Increases in the cost of oil will improve the competitive position of the LMMHD/steam system with respect to conventional oil-fired plants. The oil-fired LMMHD/steam plant has a higher generation cost than coal-fired and nuclear systems.

b. Environmental Pollution

Like the coal-fired LMMHD/steam plant the oil-fired LMMHD/steam plant reduces thermal pollution when compared with conventional steam plants, but has higher thermal pollution than some other advanced plants which are capable of higher efficiencies. The oil-fired LMMHD/steam plant has less air pollution than the coal-fired plants and the conventional oil-fired steam plants.

c. Technology, Reliability, Maintainability, and Safety

The comments regarding technology, reliability, maintainability and safety for the coal-fired LMMHD/steam plant apply for the oil-fired plant as well.

3. LMMHD/Nuclear Plants

There are no currently available, or known plans for, nuclear plants having high enough source temperatures (1800°F) to permit utilizing LMMHD as a topping plant. However, experimental reactors have been built which have temperatures approaching the temperature required. If it were possible to utilize LMMHD as a topping plant with a nuclear plant, the resulting binary plant could be superior to all other plants. The cost of nuclear plants would be reduced due to the lower capital cost of the LMMHD system. Thermal pollution would be reduced due to the higher plant efficiency.

C. GENERAL LIQUID METAL MHD TOPPING CYCLE ANALYSIS

A general parametric topping cycle analysis has been conducted to establish efficiency, power and cost trade-off parameters.

1. Efficiency Relationships

Topping and bottoming plant efficiencies can be related to give the binary plant efficiency as follows:

$$\eta_P = \frac{\eta_f}{(1 + K)} \left[\eta_T + \eta_B (1 - \eta_T + K)\right] \tag{1}$$

where

η_P = binary plant efficiency
η_f = furnace efficiency
η_T = topping cycle efficiency (without furnace)
η_B = bottoming cycle efficiency (without furnace)
K = The ratio: $\dfrac{\text{heat to steam reheater and economizer}}{\text{heat to liquid metal cycle}}$

The binary plant efficiency is shown in Fig. F-1 as a function of topping and bottoming plant efficiencies.

2. Power Relationships

The topping and bottoming plant power produced can be related to the total plant output power as follows:

$$\frac{P_T}{P_P} = \frac{\eta_T}{\eta_T + \eta_B (1 - \eta_T + K)} = \frac{\eta_T \, \eta_f}{\eta_P (1 + K)} \tag{2}$$

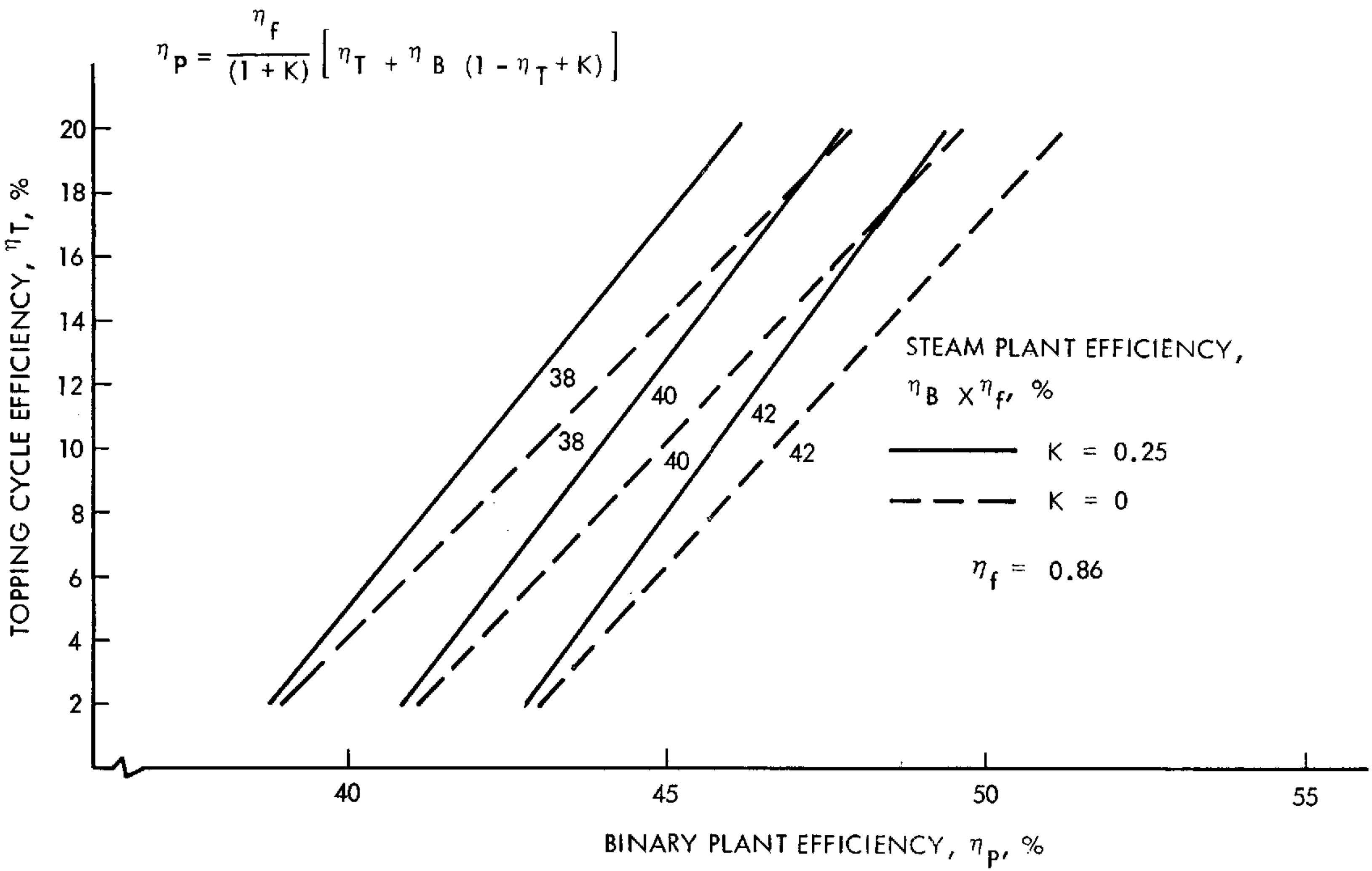

Fig. F-1. Binary plant efficiency relationship

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$$\frac{P_B}{P_P} = \frac{\eta_B (1 - \eta_T + K)}{\eta_T + \eta_B (1 - \eta_T + K)} = \frac{\eta_B \, \eta_f \, (1 - \eta_T + K)}{\eta_P \, (1 + K)} \qquad (3)$$

where

P_P = plant output power
P_T = topping plant output power
P_B = bottoming plant output power

and the efficiencies were defined above for equation (1).

Topping and bottoming plant output power are presented parametrically in Fig. F-2 as a function of topping and bottoming plant efficiencies for a total binary plant output of 1000 MW.

Cost Trade-Offs

The total power generation cost is

$$C_G = 10 \frac{\left[\left(\frac{P_T}{P_P}\right) C_T + \left(\frac{P_B}{P_P}\right) C_B\right] (F)}{8760 \ (CF)} + \frac{.0341 \ (C_{fuel})}{\eta_P} + C_{O\&M} + C_{R\&D}{}^{*} \qquad (4)$$

*Equation (4) is a simplified version of the expression used for detailed cost estimates (paragraph D). Equation (4) assumes that the liquid metal fixed cost is determined using the same annual fixed charge rate as the other capital equipment, whereas it is a nondepreciable resource subject to a lower annual fixed charge rate. Thus LMMHD capital costs will result in lower generation costs than predicted by equation (4). Also, equation (4) assumes that costs of subsystems, such as the furnace, buildings, etc., which are commonly used by the LMMHD and steam systems are apportional between the two systems. The analysis of paragraph D separates out the cost of common subsystems.

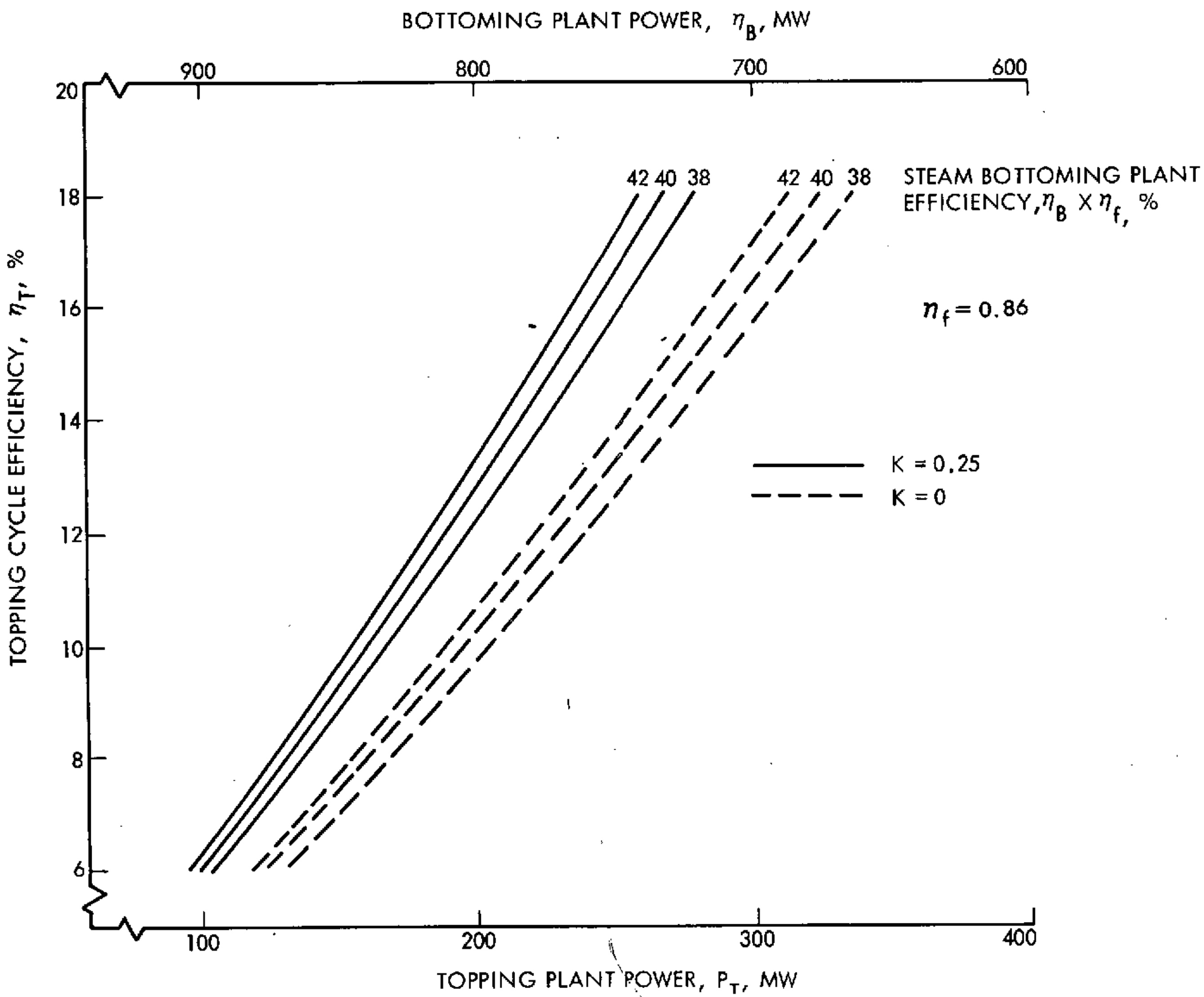

Fig. F-2. Binary plant power relationship

The terms are defined as follows with nominal values used in the parametric analysis:

- P_T, P_B, P_P = power terms defined for equations (2) and (3)

- $\frac{P_T}{P_P}$, $\frac{P_B}{P_P}$ = related as shown in Fig. F-2.

For η_T = .135, η_B = .40, η_P = .45

P_P = 1000 MW, P_T = 211 MW, P_B = 789 MW

$$\frac{P_T}{P_P} = 0.21$$

$$\frac{P_B}{P_P} = 0.79$$

- C_T = topping plant capital cost - a parameter to be varied

- C_B = bottoming plant capital cost
  = \$320/kW for coal-fired steam
  = \$230/kW for oil-fired or gasified coal-fired steam
- F = annual fixed charge
  = 15%/year
- CF = capacity factor
  = .75
- C_{Fuel} = 40 ¢/10^6 BTU for coal
  = 90 ¢/10^6 BTU for oil
  = 110 ¢/10^6 BTU for gasified coal or synthetic oil
- η_P = binary plant efficiency
  = .45

- $C_{O\&M}$ = operating and maintenance costs
  = 1.0 mills/kWh (coal-fired)
  = .80 mills/kWh (oil- and gasified coal-fired)
- $C_{R\&D}$ = amortized research and development costs
  = 0.1 mills/kWh

Using the above nominal values, power generation costs as a function of liquid metal MHD capital costs (based on 1980 costs) are shown in Fig. F-3 for a liquid metal MHD/steam binary plant. Coal-fired, oil-fired and gasified coal-fired steam plants were assumed as bottoming plants. Overlayed on the figure is the applicable power generation cost range determined by coal-fired and oil-fired steam plant costs, from Appendix B. It can be seen from the figure that, to be superior to existing plants using the same fuel, the following are the maximum capital costs permitted.

Bottoming Plant	Required LMMHD Capital Cost*, $/kW
Coal-fired	360
Oil-fired	260
Gasified coal-fired	310

*To be competitive with steam plants using the same fuel.

It is obvious that LMMHD binary plants with oil-fired and gasified coal-fired bottoming plants cannot compete as base loading plants with the coal-fired plants, due primarily to the high cost of fuel. Coal cost increases and/or environmental constraints would be required before the oil-fired or gasified coal-fired LMMHD/steam binary plants would be competitive with coal-fired power plants. Other tradeoffs are shown in Figs. F-4 through F-7 for coal- and oil-fired plants.

Figure F-5 is particularly noteworthy. It presents the trade-off between topping cycle efficiency and LMMHD capital cost. The figure shows that cycle

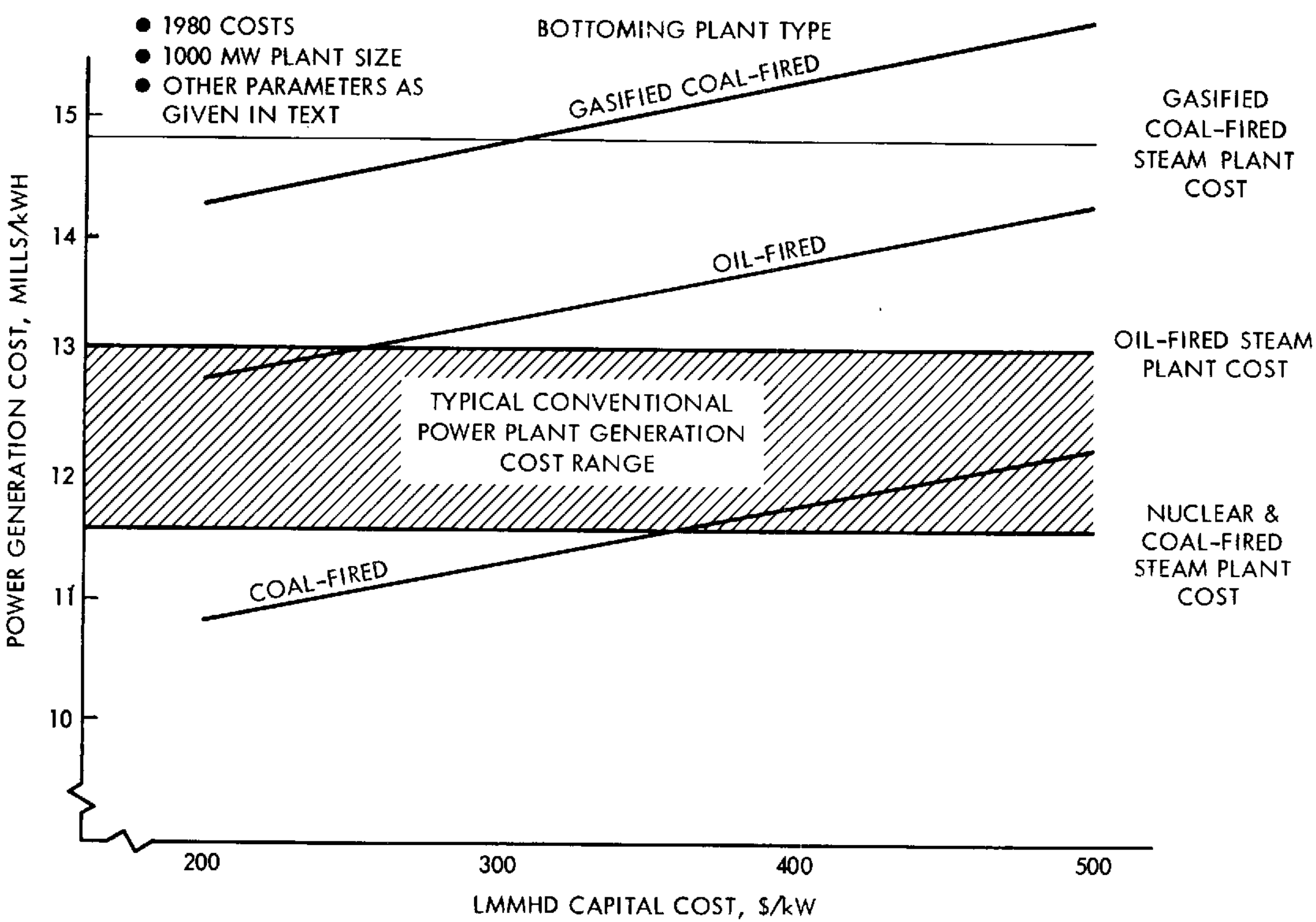

Fig. F-3. LMMHD capital cost trade off

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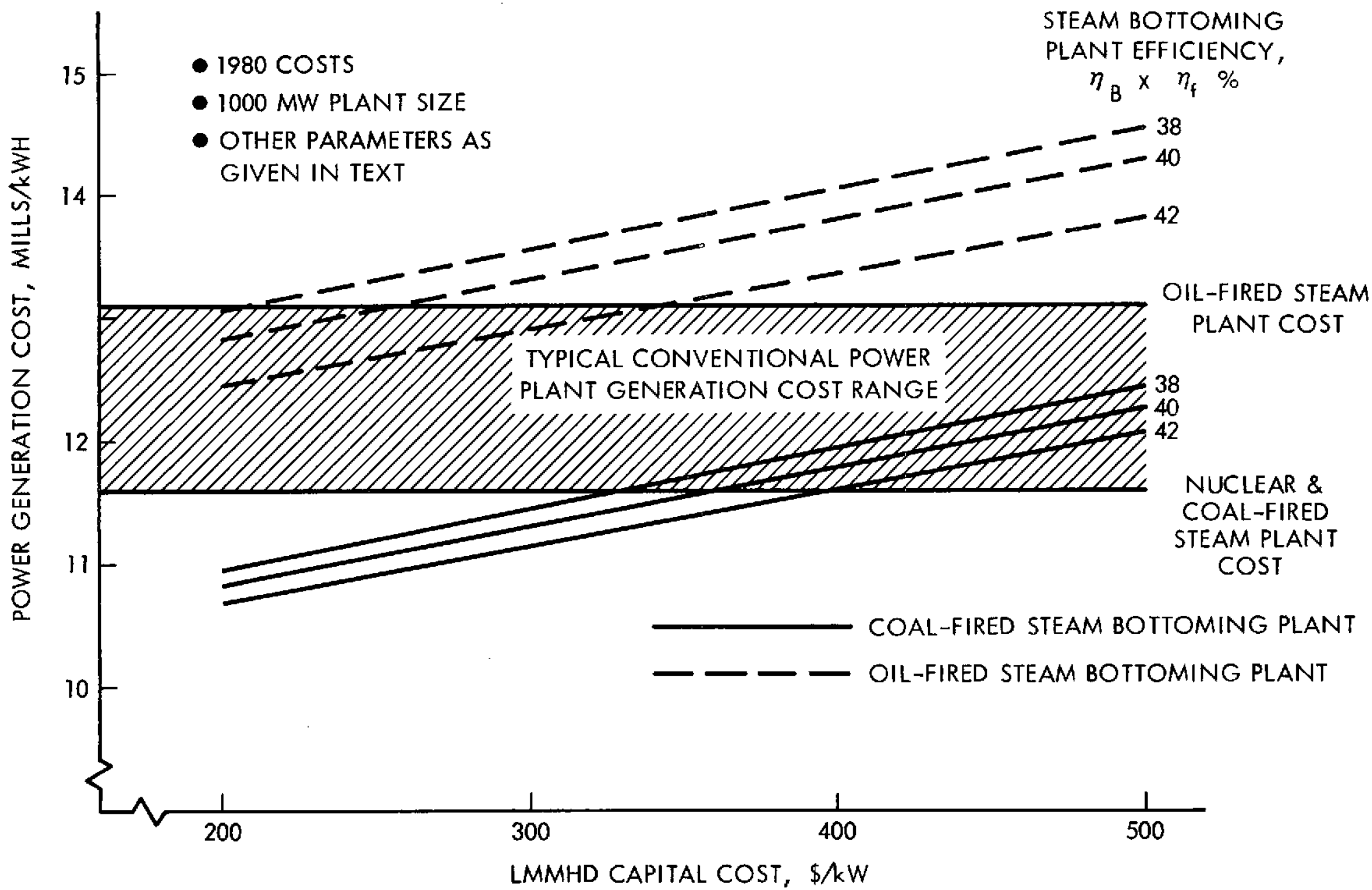

Fig. F-4. Variation in generation cost with LMMHD capital cost, steam plant efficiency and fuel type

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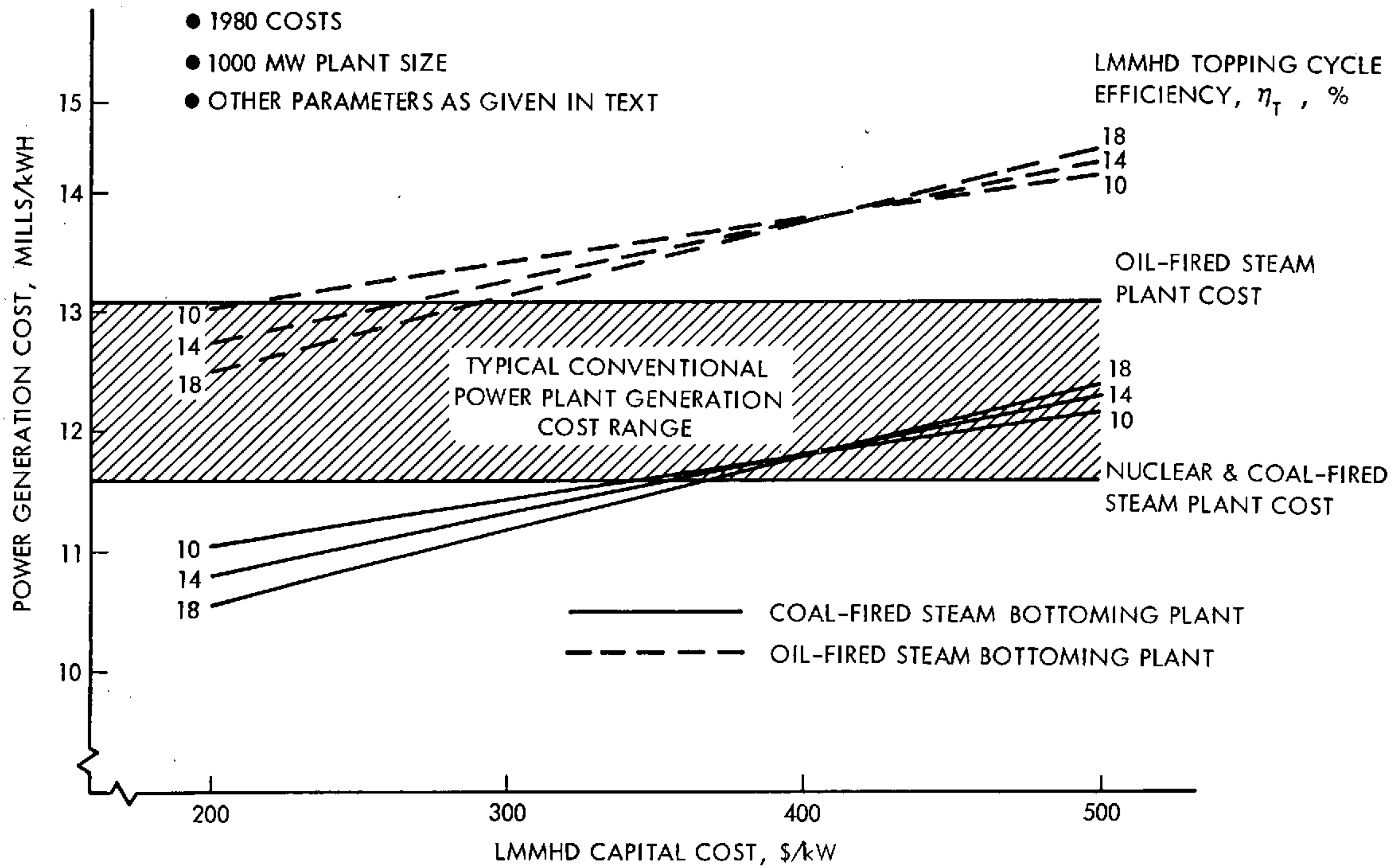

Fig. F-5. Variation in generation cost with LMMHD capital cost, LMMHD cycle efficiency, and fuel cost

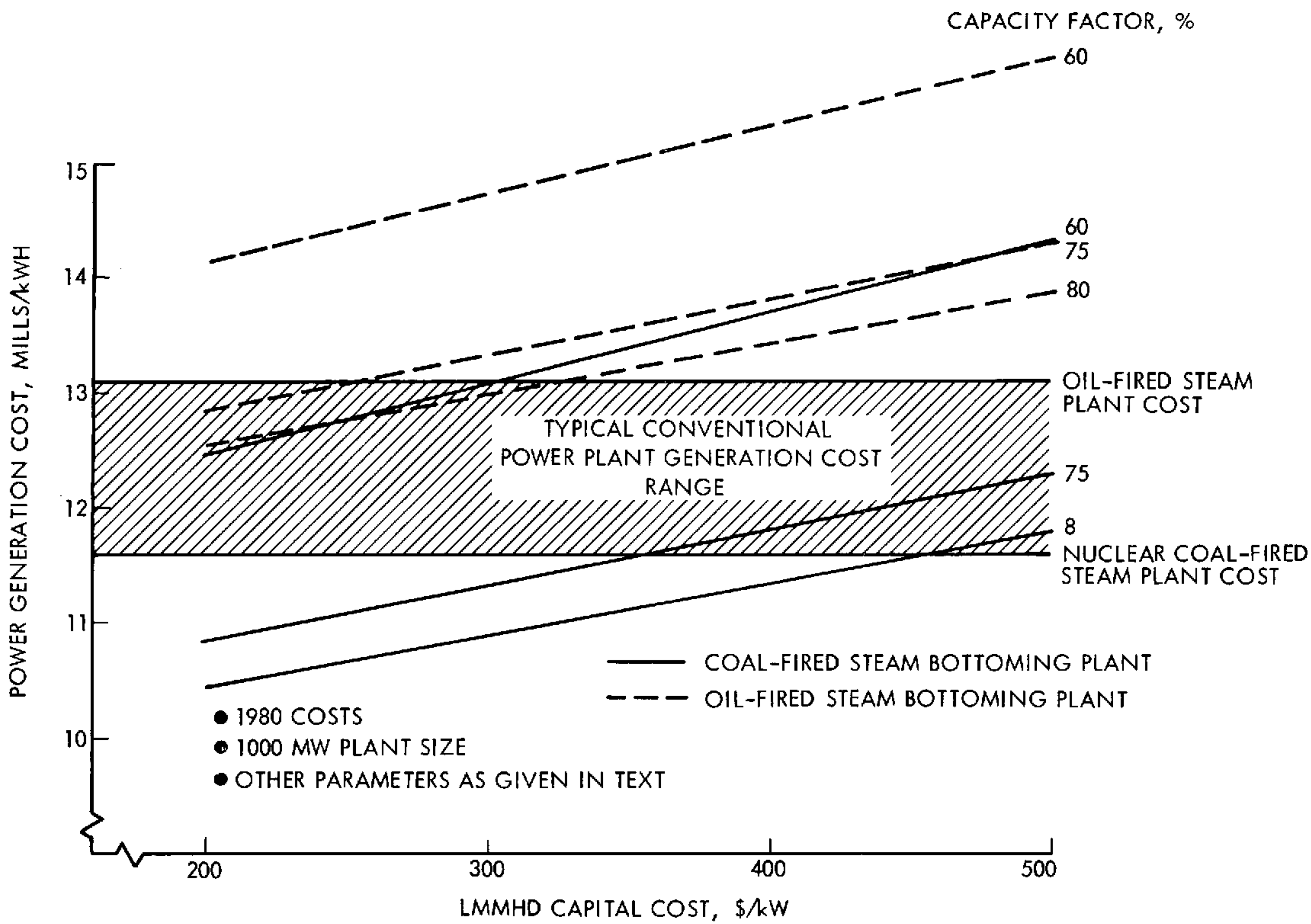

Fig. F-6. Variation in generation costs with LMMHD capital costs, capacity factor and fuel type

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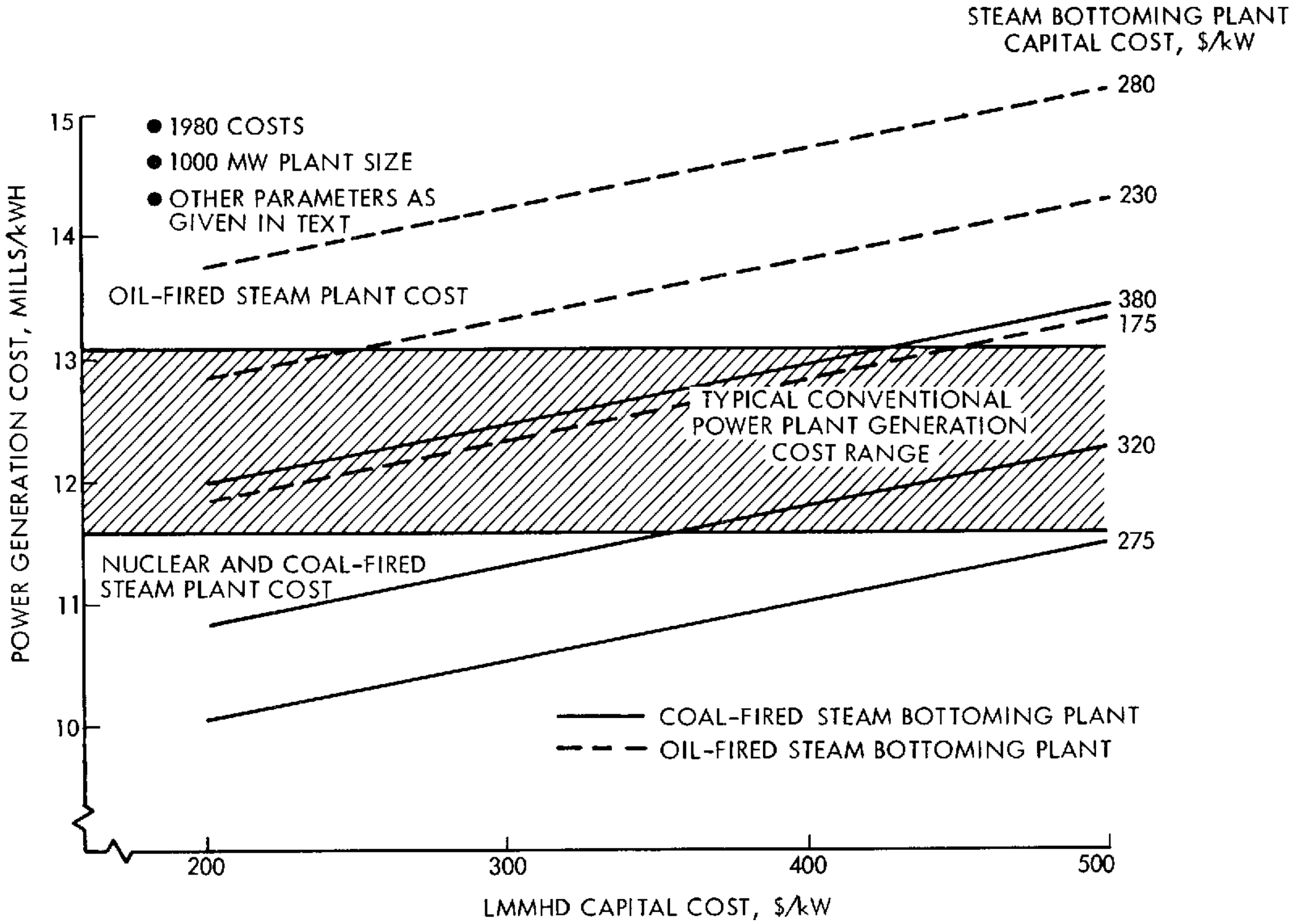

Fig. F-7. Variations in generation cost with liquid metal MHD capital cost, steam bottoming plant capital cost, and fuel type efficiency is much less important than capital cost. For topping plants with high capital cost ($400/kW and higher), improvements in efficiency actually result in higher generation cost. That is, the reduction in fuel cost is more than offset by increases in fixed cost caused by the increase in size of the topping plant as its efficiency increases. The addition of a topping plant would not be advisable under these circumstances. For lower capital costs, the reverse is true, but important cost reductions with increasing topping cycle efficiency are only achieved at low capital cost, i.e., below about $300/kW. This trade-off between capital cost and topping plant efficiency is important in determining the number of LMMHD topping plant stages and the system design.

It should also be pointed out that increases in topping plant component efficiencies, which provide overall binary plant efficiency increases, produce more power for the same capital cost, thus reducing the specific capital cost. The primary cost benefit in this case would be derived from the capital cost reductions rather than the fuel cost reductions due to efficiency improvement. For a coal-fired bottoming plant, for example, a 2% decrease in efficiency at a capital cost of $250/kW can be offset by a reduction of only about $10/kW of liquid metal MHD capital cost. The significance of this trade-off is discussed in Appendix E where it is shown that it is far better to design a two stage liquid metal MHD topping plant, rather than a plant with three or more stages. The efficiency is reduced slightly but the liquid metal MHD capital cost, and thus the total power generating cost, are consequently reduced significantly.

From Figs. F-6 and F-7, it is obvious that the capacity factor and bottoming plant capital costs significantly effect the generation costs. The capacity factor should be as high as possible by achieving high reliability and low maintenance requirements. Specifically, the liquid metal MHD/steam binary plant must have at least 0.70 capacity factor to be competitive with other systems and probably would require a higher capacity factor to be a superior system.

D. COST EVALUATION

The cost evaluation includes determination of power generation costs for the LMMHD/steam binary plant and comparison with alternative systems.

Applications for which the LMMHD/steam binary system has cost advantages are identified. Also, applications under alternative fuel availability scenarios are considered.

1. LMMHD Capital Costs

Basic 1980 LMMHD costs were presented in Appendix E as follows:

Capital cost without liquid metal	- \$219/kW
Capital cost of liquid metal	- \$ 63/kW
Total Capital cost	- \$282/kW

These costs were established based on state-of-the-art assumptions. Alternative designs have been postulated in Appendix E which indicate that capital cost improvements of 25% could be achieved through the use of different liquid metal ratios and substitute materials. Further cost improvement can possibly be achieved by improvements in separator design. It has been estimated that the combined effect of the design improvements would reduce the 1980 capital cost to about \$185/kW.

The above LMMHD capital costs, when combined with steam bottoming plant costs, yield the following binary plant costs, shown in comparison with conventional steam plant capital costs.

Fuel	LMMHD/Steam Plant Capital Cost	Steam Plant Capital Cost
Coal	311	320
Oil/gas	241	230

The above calculated capital costs do not consider that the liquid metal is a nondepreciable resource or that efficiency advantages of the LMMHD/steam binary plant will reduce plant size and fuel cost. These factors are included in the calculation of the power generation costs (see subsection 3).

2. Efficiency

The LMMHD cycle efficiency was established in Appendix E as 13.5% for a two-stage system. It is possible that the efficiency could be increased to 16% with separator performance improvements as discussed in Appendix C. Also, it is possible that system optimization to reduce the capital cost by changing the liquid metal ratio will also reduce the cycle efficiency. For the purposes of this analysis 13.5% LMMHD cycle efficiency is used.

The corresponding LMMHD/steam binary plant efficiency was calculated according to equation (1) in paragraph C of this Appendix. The binary plant efficiency was calculated as 45%, assuming a steam plant efficiency of 40%, a furnace efficiency of 86% and 0.25 as the ratio of heat to the steam reheater and economizer/heat to the LMMHD cycle.

3. Power Generation Costs for the LMMHD/Steam Binary Plant

The power generation costs for the LMMHD/steam binary system were determined using the same methods as described for alternative systems in Appendix B and as used in the general topping cycle analysis given in paragraph D of this Appendix. The analysis was refined somewhat, however. One change in the calculation resulted from the liquid metal being a nondepreciable resource. That is, the lithium could be reused in another liquid metal plant or in a fusion reactor at the end of the lifetime of the first plant. Thus, the annual fixed charge applied to the liquid metal has been reduced from 15% to 10%, by eliminating the depreciation costs and assuming that the bond interest is reduced by about one-half.

Another change from the previous method of calculation is that the bottoming plant capital costs have been separated from the costs of plant components that are used in common by the topping and bottoming plant. The power generation cost for the LMMHD/steam binary plant thus becomes:

$$C_G = \frac{10\left[\left(\frac{P_T}{P_P}\right)\ (C_T F_1 + C_{LM}\ F_2) + \left(\frac{P_B}{P_P}\right) C_B F_1 + C_A F_1\right]}{8760\ (CF)}$$

$$+ \frac{.03413\ C_{FUEL}}{\eta_P} + C_{O\&M} + C_{R\&D}$$

The terms are as follows, with the nominal values used to determine the LMMHD/steam plant generation costs.

P_T = topping plant power, MW

P_B = bottoming plant power, MW

P_P = binary plant power, MW

$\frac{P_T}{P_P}$ = 0.211

$\frac{P_B}{P_P}$ = 0.789

C_T = LMMHD topping plant capital cost without liquid metals
= \$219/kW

C_{LM} = liquid metal capital cost
= \$63/kW

C_B = bottoming plant capital cost
= \$160/kW for all fuels

C_A = capital cost of land, buildings, furnace, draft equipment, fuel handling, etc.
= \$140/kW for coal*
= \$60/kW for oil-, and gasified coal-fired*

*The sum of C_B and C_A is less than for conventional plants. C_A has been assumed to be reduced as a result of increased plant efficiency. That is, the capital costs of components comprising C_A would remain constant while the plant power is increased, thus reducing the specified capital cost, C_A. Similar assumptions were made for the other advanced binary plants.

F_1 = annual fixed charge for everything except the liquid metals
= 15%/year

F_2 = annual fixed charge for the liquid metals
= 10%/year

(CF) = capacity factor
= 0.75 (coal-fired)
= 0.775 (oil-fired, and gasified coal-fired)

C_{FUEL} = 40¢/10^6 BTU for coal
= 90¢/10^6 BTU for oil
= 110¢/10^6 BTU for gasified coal or synthetic oil

η_P = binary plant efficiency
= 45%

$C_{O\&M}$ = operations and maintenance costs
= 1.0 mills/kWh for coal-fired plants
= 0.8 mills/kWh for oil- and gasified coal-fired plants

$C_{R\&D}$ = amortized research and development costs
= 0.1 mills/kWh

The generation costs for the LMMHD/steam binary plant are then as follows:

Bottoming Plant	Generation Costs
Coal-fired	11.4
Oil-fired	13.0
Gasified coal-fired	14.6

4. Comparison of the LMMHD/Steam Binary Systems with Alternative Systems

The generation cost determined above were overlayed on the alternative system costs presented in Appendix B as shown in Figs. F-8 and F-9. Figure F-8 compares the LMMHD/steam plant with conventional power plants. Figure F-9 shows the LMMHD/steam plants compared with advanced power

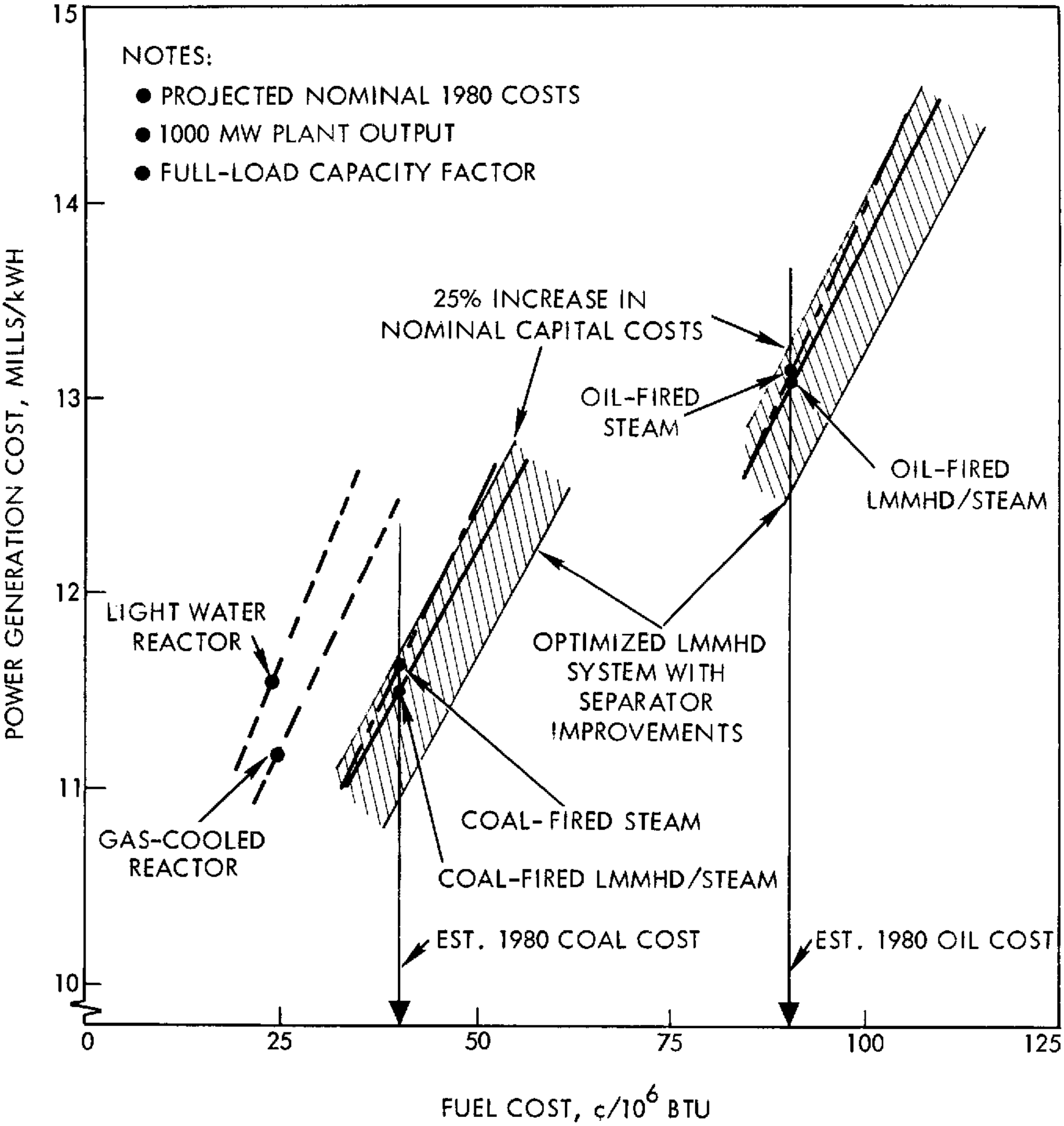

Fig. F-8. Comparison of power generation costs between conventional power plants and LMMHD/steam plants

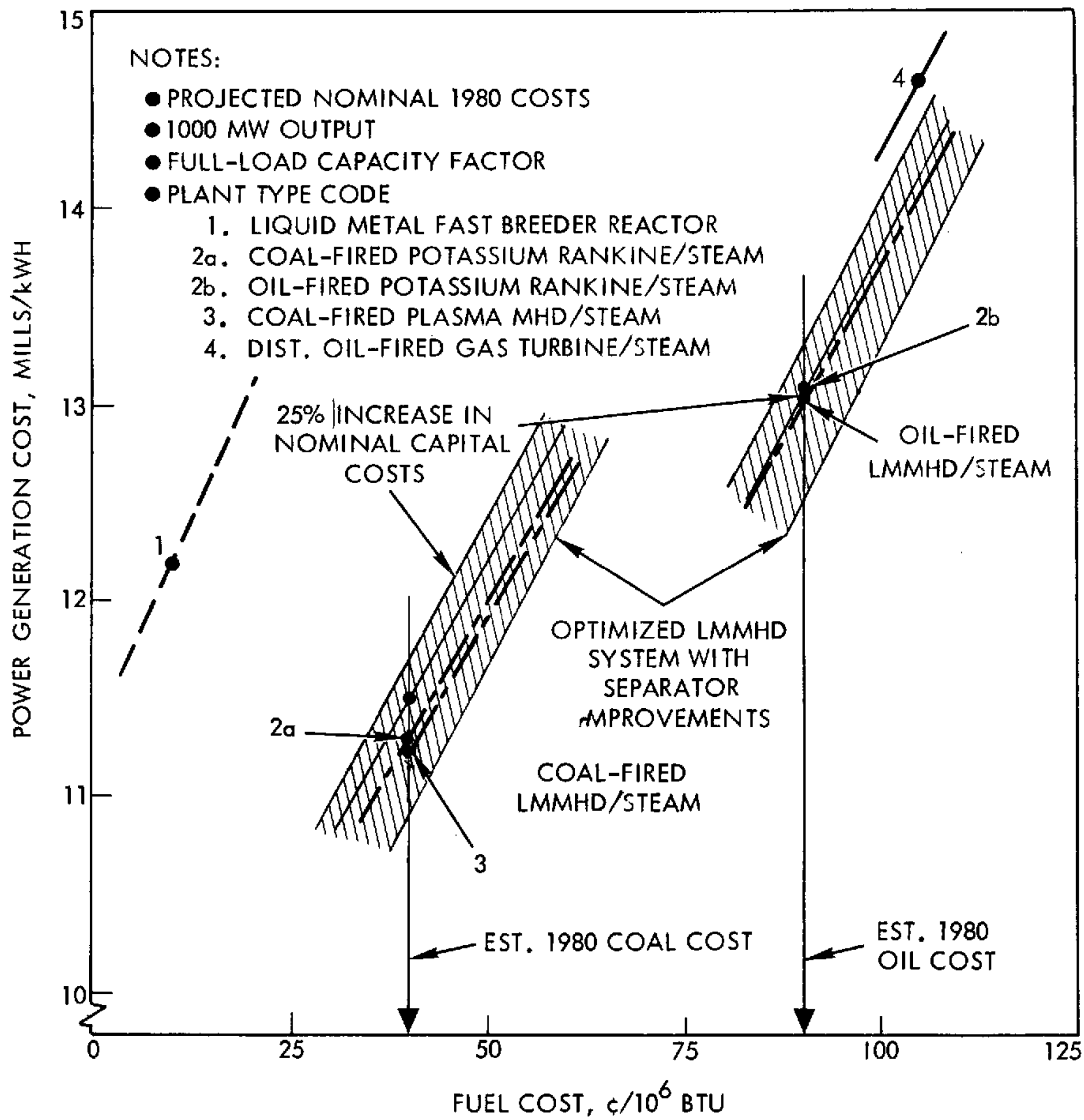

Fig. F-9. Comparison of power generation costs between advance power plants and LMMHD/steam plants

plants. The figures show the nominal 1980 generation costs for 1000 MW plants. Variations of these nominal costs with changes in fuel cost are indicated. The LMMHD/stea m plant nominal values are shown with a range of costs. The lower limit represents an optimized system; the upper limit represents capital costs 25% greater than the nominal values, which is extremely conservative. Adding Cb-1%Zr sheet to the entire system, for example, only increases the capital cost by about 11%. The following can be concluded from Fig. F-8.

The coal-fired LMMHD/steam binary plant has the potential for economic improvement over conventional coal-fired and nuclear plants of 0.2 to 0.6 mills/kWh. This cost reduction is due to the efficiency improvement at low capital cost. The annual cost savings for a 1000 MW coal-fired LMMHD/steam binary plant derived from the nominal cost differential from a conventional coal-fired plant shown in Fig. F-8 is about $1 million. At a 15% annual fixed charge rate, this is equivalent to about a $7 million capital cost reduction. If the optimized system proves to be achievable, the annual savings would be about $4.5 million for a 1000 MW system.

The oil-fired LMMHD/steam plant has potential nominal 1980 power generation costs 0.1 to 0.6 mills/kWh lower than the conventional oil-fired plant. Corresponding LMMHD/steam plant annual cost savings compared with the conventional oil-fired steam plant would be $0.5 to $4.5 million for a 1000 MW plant.

As fuel costs increase, the power generation cost of the LMMHD/steam plant will be reduced even more with respect to the conventional plants due to the higher efficiency of the LMMHD/steam plant.

The following can be concluded from Fig. F-9:

1) The LMMHD/steam plant has nominal generation costs comparable to the plasma MHD/steam plant and the potassium Rankine/steam plant.

2) The LMMHD/steam plant has lower generation costs than the gas turbine/steam plant.
3) Considering the uncertainties in advanced systems' generation costs the LMMHD/steam plant has the potential of achieving lower generation costs than any of the other advanced systems considered.

Although not shown in Figs. F-8 or F-9, LMMHD combined as a topping cycle with an advanced nuclear plant (if the required temperatures could be achieved) could provide for significant cost reduction due primarily to reductions in specific capital cost, and secondarily to improved plant efficiency.

5. Cost Influence Coefficients

Influence coefficients have been generated for both the coal- and oil-fired LMMHD/steam systems as shown in Table F-1. These may be used to calculate generation cost changes from the nominal with changes in the principle parameters affecting costs.

6. Alternative Fuel Scenarios

a. Nuclear Power Restriction

Nuclear power restrictions due to environmental constraints would probably increase the requirements for fossil fuel-fired systems. An increase in the need for fossil fueled systems could result in increased fuel prices which would favor the application of LMMHD.

b. Coal Restrictions

If the use of coal were restricted (except for gasified coal) due to environmental constraints, the application of nuclear power would probably be increased. The LMMHD topping plant would be deprived of one of its primary applications. The use of oil and gasified coal would probably increase and fuel prices would probably rise. Oil-fired LMMHD/steam plants would provide increasingly lower generation costs, when compared to conventional oil-fired systems, as

Table F-1. LMMHD/steam plant cost influence coefficient

Influence Coefficient	Coal-Fired LMMHD/ Steam Plant	Oil-Fired LMMHD/ Steam Plant
1. $\frac{\partial C_G}{\partial C_T} = \left(\frac{10}{H}\right)\left(\frac{P_T}{P_P}\right) F_1 \; \frac{\text{mills}}{\$\,\text{h}}$ (Multiply by change in C_T, \$/kW, to get change in C_G, mills/kWh)	0.0048	0.00465
2. $\frac{\partial C_G}{\partial C_{LM}} = \left(\frac{10}{H}\right)\left(\frac{P_T}{P_P}\right) F_2 \; \frac{\text{mills}}{\$\,\text{h}}$ (Multiply by change in C_{LM}, \$/kW, to get change in C_G, mills/kWh)	0.0032	0.0031
3. $\frac{\partial C_G}{\partial C_B} = \left(\frac{10}{H}\right)\left(\frac{P_B}{P_P}\right) F_1 \; \frac{\text{mills}}{\$\,\text{h}}$ (Multiply by change in C_B, \$/kW, to get change in C_G, mills/kWh)	0.018	0.0175
4. $\frac{\partial C_G}{\partial C_A} = \frac{10\, F_1}{H}, \; \frac{\text{mills}}{H}$ (Multiply by change in C_A, \$/kW, to get change in C_G, mills/kWh)	0.0228	0.0228
5. $\frac{\partial C_G}{\partial F_1} = \left(\frac{10}{H}\right)\left[\left(\frac{P_T}{P_P}\right) C_T + \left(\frac{P_B}{P_P}\right) C_B + C_A\right], \; \frac{\text{mills yr}}{\text{kWh}}$ (Multiply by change in F_1, %/yr, to get change in C_G, mills/kWh)	0.46	0.327
6. $\frac{\partial C_G}{\partial F_2} = \left(\frac{10}{H}\right)\left(\frac{P_T}{P_P}\right) C_{LM} \cdot \frac{\text{mills yr}}{\text{kWh}}$ (Multiply by change in F_2, %/yr, to get change in C_G, mills/kWh)	0.0203	0.0196
7. $\frac{\partial C_G}{\partial H} = \frac{10}{H^2}\left\{\frac{P_T}{P_P}\left[C_T F_1 + C_{LM} F_2\right] + \left(\frac{P_B}{P_P}\right) C_B F_1 + C_A F_1\right], \; \frac{\text{mills yr}}{\text{kWh}^2}$ (Multiply by change in h, h/yr, to get change in C_G, mills/kWh)	-1.08×10^{-3}	-0.777×10^{-3}
8. $\frac{\partial C_G}{\partial C_{FUEL}} = \frac{.03413}{\eta_P} \cdot \frac{\text{mills BTU}}{4\ \text{kWh}}$ (Multiply by change in C_{FUEL}, ¢/10^6 BTU to get change in C_G, mills/kWh)	0.076	0.0735
9. $\frac{\partial C_G}{\partial \eta_T} = \frac{10}{H}\left\{\left[\frac{\eta_B\,(1+K)}{[\eta_T + \eta_B\,(1-\eta_T + K)]^2}\right]\left[C_T F_1 + C_{LM} F_2 - C_B F_1 - C_A F_1\right]\frac{(1-\eta_B)}{[\eta_T + \eta_B(1-\eta_T+K)]}\right\}^{*} - \frac{.03413\, C_{FUEL}\, \eta_F\,(1-\eta_B)}{\eta_P^{\,2}\,(1+K)}, \; \frac{\text{mills}}{\text{kWh}}$ (Multiply by change in η_T, %/100, to get change in C_G, mills/kWh)	-3.59	-5.03
10. $\frac{\partial C_G}{\partial \eta_B} = -\frac{10}{H}\left\{\left[\frac{\eta_T\,(1-\eta K)}{[\eta_T + \eta_B\,(1-\eta_T+K)]^2}\right]\left[C_T F_1 + C_{LM} F_2 - C_B F_1\right] + \frac{C_A F_1\,(1-\eta_T+K)}{[\eta_T + \eta_B\,(1-\eta_T+K)]}\right\}^{*} - \frac{.03413\, C_{FUEL}\,(1-\eta_T+K)}{\eta_P^{\,2}\,(1+K)}, \; \frac{\text{mills}}{\text{kWh}}$ (Multiply by change in η_B, %/100, to get change in C_G, mills/kWh)		

*Assumes C_C inversely proportional to plant efficiency, η_P

Table F-1 (Contd)

Definition of Symbols

C_G = generation cost, mills/kWh

C_T = topping plant capital cost, $/kW

C_{LM} = liquid metal capital cost, $/kW

C_B = bottoming plant capital cost, $/kW

C_A = capital cost of plant components used commonly by the topping and bottoming plant, i.e., furnace, buidings, etc., $/kW

C_{FUEL} = fuel cost, ¢/10^6 BTU

F_1 = annual financial charge for everything except liquid metal, %/yr

F_2 = annual financial charge for the liquid metal, %/yr

H = average hours on line per year, h/yr

P_T = topping plant power output, MW

P_B = bottoming plant power output, MW

P_P = binary plant power output, MW

η_T = topping cycle efficiency

η_b = bottoming cycle efficiency

η_f = furnace efficiency

η_P = binary plant efficiency

$\eta_T \eta_f$ = topping plant efficiency

$\eta_B \eta_f$ = bottoming plant efficiency the fuel cost increased. Also, if a high temperature nuclear reactor were developed, the LMMHD topping plant could be advantageously coupled with it.

c. Oil Restrictions

Oil restrictions due to import constraints would probably increase the application of coal-fired and nuclear plants and raise the price of oil. All of these factors would favor the application of LMMHD topping cycles.

d. Nuclear and Coal Restrictions

Nuclear and coal restrictions would probably result in increased use of oil and gasified coal. LMMHD topping cycles would become increasingly attractive as the oil prices rise.

e. Nuclear, Coal and Oil Restrictions

Restrictions of nuclear, coal and oil plants would probably increase the use of gasified coal or synthetic oil. Fuel prices would rise, and advanced power systems having high efficiency would be favored. The LMMHD/steam plant would have lower generation costs than conventional gas-fired plants.

E. ENVIRONMENTAL EVALUATION

Environmental pollution is a function of fuel type, plant design and efficiency. The following analysis evaluates the environmental effects of a LMMHD/steam binary plant in comparison with the alternative systems described in Appendix B. Air pollution and thermal pollution are considered.

1. Air Pollution

The major air pollutants produced by fossil-fuel plants are particulates, oxides of sulfur, and oxides of nitrogen. The production of these pollutants for conventional plants was given in Appendix B. The emissions produced per unit of electrical output are affected by plant design, combustion processes and plant efficiency.

While it is not within the scope of this study to evaluate plant design and combustion processes, it is likely that LMMHD and other advanced binary plants will reduce plant emissions (other than oxides of nitrogen) by a decrease in fuel usage.

The bar graph of Fig. F-10 shows that the LMMHD/steam binary system significantly reduces the above air pollutants when compared to a conventional system. However, the other advanced systems, because of their higher efficiencies, reduce the pollutants somewhat more. The figure can be used to estimate the air pollution reduction from advanced plants for different fossil fuels by multiplying the air pollutant values given in Appendix B, paragraph D, by the factors in Fig. F-10. As an example Fig. F-11 presents the annual production of oxides of sulfur for various plant types as determined from Fig. F-10 and Table B-19 (Appendix B). Note that the maximum air pollution reduction, for any specific fuel, due to reduction in power plant fuel usage is about 20%. For larger reductions in air pollution, modifications of the combustion process, fuel processing, stack gas cleansing, etc., would be required.

The level of NO_x emissions from steam plants is related to burner design, boiler design, and control of the combustion process. Attention to each of these factors will be necessary to control NO_x emissions to acceptable levels. Emissions of NO_x are generally lowered by either reducing the available oxygen in the flame, or by reducing peak combustion temperatures. In existing steam plants, low-NO_x operation is achieved by low excess air firing (for coal) or by fuel-rich burner operation followed by controlled addition of the remaining combustion air (for gas and oil). Product gas recirculation, a technique which lowers peak flame temperatures, can also be used to lower NO_x production as shown in Fig. F-12.

The main difference between a steam system with a topping cycle and a conventional steam plant is the higher mean temperatures required in the liquid metal tube wall.

The mean temperatures required are not sufficiently high to produce NO_x in themselves, even in the presence of large amounts of oxygen. Careful

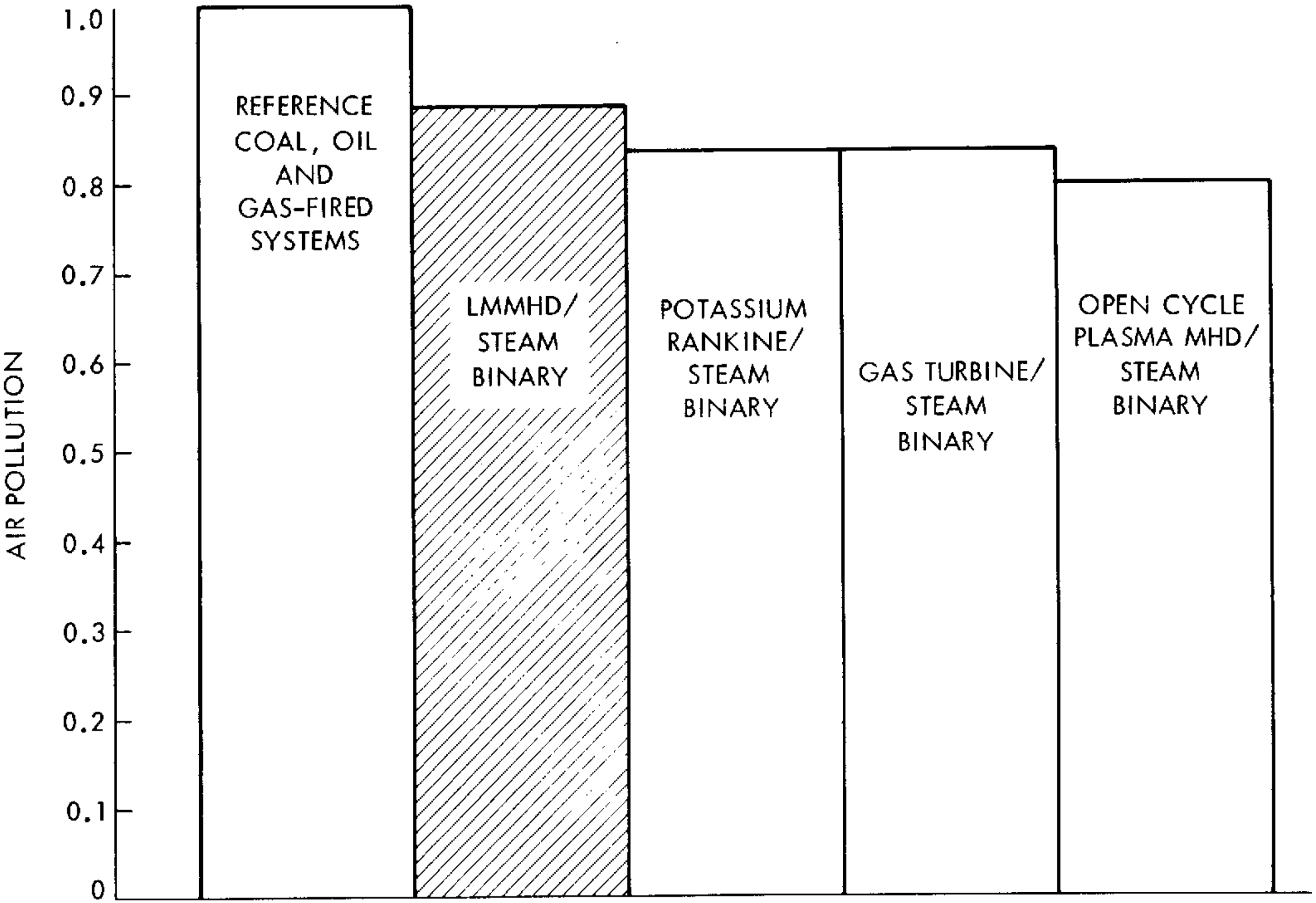

Fig. F-10. Air pollution (except NO_x)

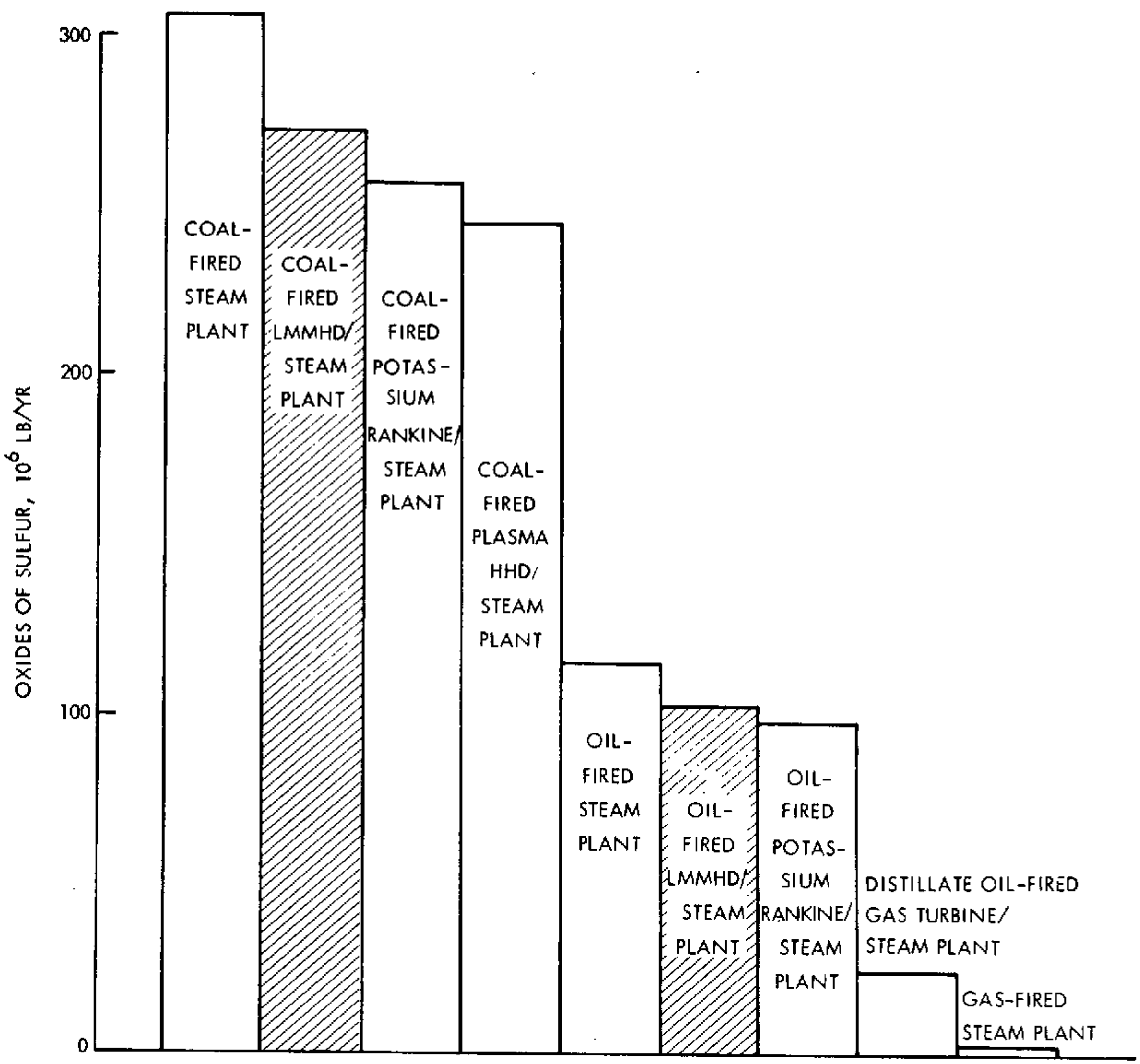

Fig. F-11. Annual production of oxides of sulfur from 1000 MW power plants

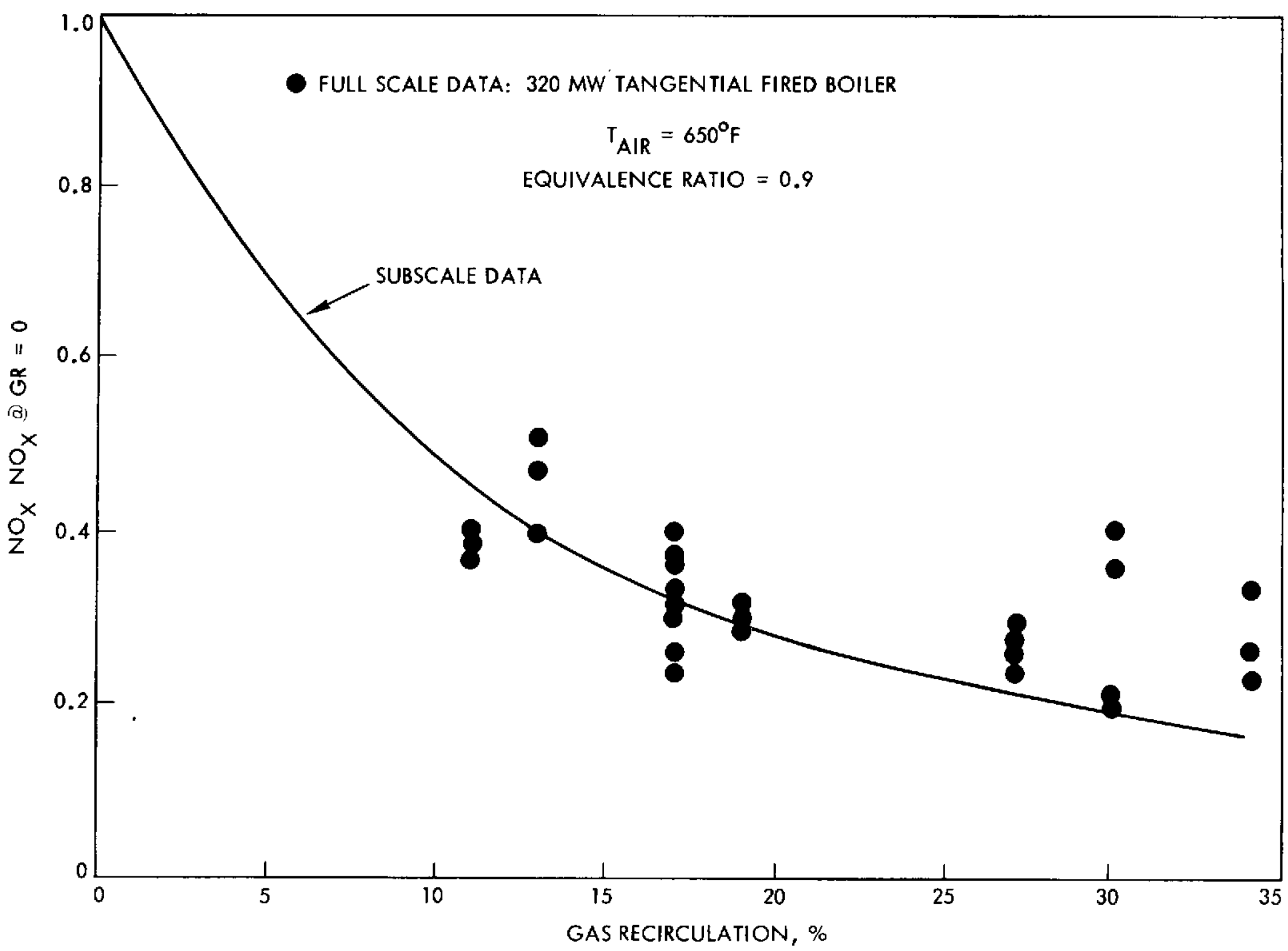

Fig. F-12. NO_x emissions vs gas recirculation (natural gas fuel) control of the combustion process will be needed, however, to prevent increased local flame temperatures that would produce large amounts of NO_x. In addition, modified boiler design may be needed to increase heat transfer in the hottest combustion zones. Further work should include detailed analysis of NO_x emissions.

2. Thermal Pollution

The heat rejected by a power plant is related to the output power and plant efficiency as follows:

$$Q_R = \frac{P\,(1 - \eta_P)}{\eta_P}$$

where

Q_R = heat rejected

P = output power

η_P = plant efficiency

The thermal pollution has been calculated for the LMMHD/steam binary plant in comparison with the competing systems, assuming equal power outputs of 1000 MW. The competing system efficiencies used were from Appendix B and the LMMHD efficiency was from Appendix E.

System	Efficiency
1. Coal-fired steam	40
2. Oil-fired steam	40
3. Open cycle plasma MHD/fossil fuel steam	50
4. Gas turbine/fossil fuel steam	48
5. Potassium Rankine/fossil fuel steam	48
6. Light water nuclear reactor	33
7. Gas-cooled thermal nuclear reactor	39
8. Liquid metal fast breeder reactor	40
9. LMMHD/steam	45

Figure F-13 shows the thermal (combined air and water) pollution produced by the LMMHD/steam plant and the alternative systems. The LMMHD/steam binary plant is seen to produce significantly less thermal pollution than conventional plants, but somewhat more than other advanced systems which have higher plant efficiencies.

F. TECHNOLOGY EVALUATION

The status of the technology of liquid metal MHD and the alternative systems is assessed in this section. Conventional systems, while continuing to be improved, are currently developed and require no technology advancements to make them viable. These systems are:

1) Coal-fired steam plant.
2) Oil/gas-fired steam plant.
3) Light water nuclear reactor plant.
4) High temperature gas-cooled thermal nuclear reactor plant.
5) Gas turbine/steam binary plant.

The advanced plants which require technology advances to achieve a commercial status are

1) Open cycle plasma MHD/steam binary plant.
2) Potassium Rankine/steam binary plant.
3) Liquid metal fast breeder nuclear reactor plant.
4) Liquid metal MHD/steam binary plant.

The following paragraphs summarize the technology development requirements for each of the advanced systems, including the gas turbine steam binary plant which has significant growth potential.

1. Open Cycle Plasma MHD/Steam Binary Plant

Technology problems associated with the development of open cycle plasma MHD have been reported in several references, e.g., Refs. F-1 and

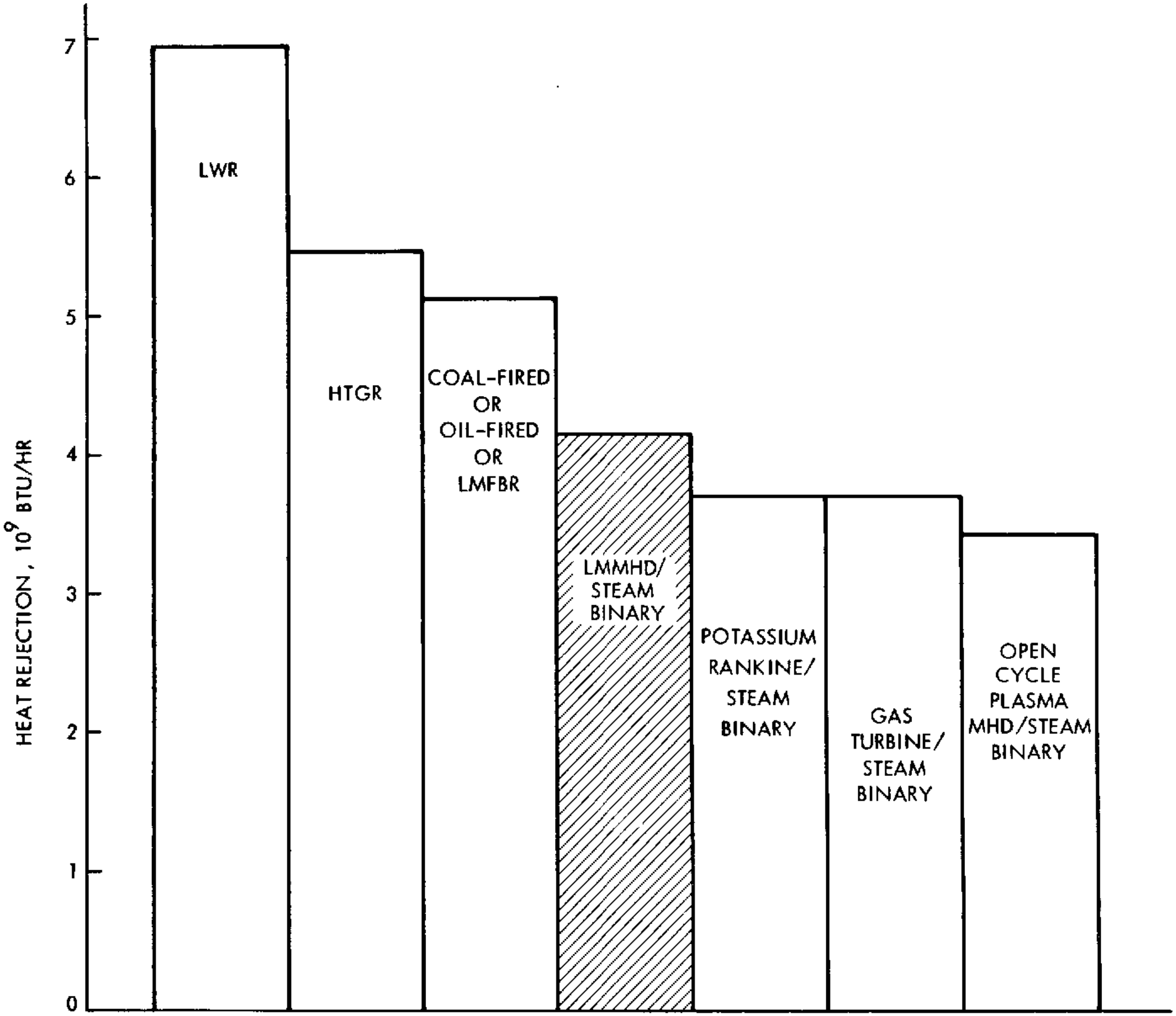

Fig. F-13. Thermal pollution

F-2. For a coal-fired system, the following is a summary of technology problems requiring future work (summarized from Ref. F-1). The fundamental problem areas are

1) Materials.
2) Generator performance.
3) Gas conductivity and combustion.
4) Seed recovery.

Specifically, the problems to be resolved are as follows.

Very high temperature, thermal cycling and long duty cycles present a severe environment for materials and cause potential materials compatibility problems. Primary problem areas are in air preheaters, electrodes and insulators. Significant materials work is also required in nozzles, valves, ducts and boiler tubes.

Improvement in generator performance is required beyond simple scaling of existing techniques. Areas of work include: generator configuration and loading, thermal viscous losses, electrode and insulator wall breakdown, electrode losses and voltage drops, and electrical and aerodynamic stability of the generator.

Development is required to enable prediction of electrical conductivity of the hot gasses to achieve the required 5% uncertainty in power output.

In the area of combustion techniques, further development is required to achieve the very high temperatures needed without oxygen enrichment while minimizing heat loss. For coal-fired plants, techniques for ash and slag removal from the MHD channel without loss of seed in the slag requires development.

A high degree of seed recovery is required (at least 98% to be economical), while also controlling air pollutants.

2. Gas Turbine/Steam Binary Plant

Of all the advanced plants considered, the development of the gas turbine/steam binary plant has progressed the furthest. Combined cycle plants, as they are called, having mid-range power capability, are now being installed for swing plant application. These plants presently have efficiencies nearly comparable to oil plants, higher specific capital cost, but reduced air pollution. A primary technical challenge of the future will be to increase plant efficiency, primarily by increasing turbine inlet temperature and compressor pressure ratio. Future efficiencies of over 50% are predicted (Refs. F-1 and F-3).

The technical challenges to achieve advanced, high performance, designs for gas turbines include the need for turbine, compressor and combustion materials development, and turbine blade cooling. An advantage for the gas turbine power plant development is that the technology being developed for advanced aircraft turbine engines is directly applicable. Hence, solutions to the materials and turbine cooling problems have been postulated as follows.

Gains in turbine blade materials have been most significant with nickle-base alloys. These materials have been designed for relatively short life; however, modified heat-treatment cycles promise to improve their life. Turbine blade materials to achieve the performance used in this study will include high-temperature nickle-base alloys currently under development for advanced aircraft gas turbines.

Chromium-base alloys and columbium base alloys offer possibility for application to achieve even higher turbine inlet temperatures and efficiencies. For turbine vanes, a cobalt-base alloy has been the primary material used. Corrosion resistance for turbine blade and vanes is provided by coatings. It has been predicted that increased thickness of the coatings will provide the required lifetimes for utility power applications.

To achieve improved compressor performance, efforts to develop light-weight stiff blades, permitting increased aspect ratios, will be necessary. Fiber-reinforced composite materials appear promising for this application.

Combustor materials required to achieve the high performance predictions in this study could include materials such as Hastelloy X or coated TD nickle. Further improvements in performance would require coated refractory materials.

To achieve the performance used in this study, advanced impingement convection cooling techniques would be required. (Transpiration cooling would be required for turbine inlet temperatures above 2400°F.)

Even though there are very significant development problems facing the high performance gas turbine/steam combined cycle plant, its development is more certain than some other advanced systems because (1) this type of plant is currently being marketed commercially, and (2) improvements being developed for the aircraft industry can be applied.

3. Potassium Rankine/Steam Binary Plant

The potassium Rankine system has undergone considerable development work at the General Electric Company and NASA Lewis Research Center (for space applications) with some related research conducted at Oak Ridge National Laboratory. Small complete systems have been operated for extensive periods of time (about one year). It is possible with technology and designs known today, using conventional stainless steel materials, that potassium Rankine/steam binary plants could be constructed with plant efficiencies of about 45%. These have been referred to in this study as low temperature systems.

To achieve higher efficiency, higher turbine inlet temperatures are required. This will necessitate using advanced materials such as coated TD nickle or columbium. This materials problem is similar to other advanced high temperature systems' materials problems discussed here. Primary problems encountered in the development to date have been with turbine blade erosion and seals. Turbine blade erosion, particularly with multiple turbine stages and increasing moisture content in the latter stages will continue to be a developmental problem. Liquid metal handling also presents a potential safety hazard. An advantage this system has over MHD systems is that system performance has been fairly well established, whereas MHD system performance requires demonstration. A disadvantage for this system is that relatively little research and development is currently underway.

4. Liquid Metal Fast Breeder Reactor (LMFBR) Plant

There is considerable development effort on-going for the liquid metal fast breeder reactor, i.e., about $100 million/year by the AEC. Some of the major problems to be confronted (Refs. F-1, F-2, and F-4) are the following:

1) Core stability - The sodium void reactivity coefficient is positive so that a loss of sodium coolant leads to a neutron multiplication constant greater than unity. A superior control and sensing system must be developed. A core design must be developed to prevent sodium voids and other possible malfunctions from spreading throughout the core. However, economic penalties result from design alternatives to the positive void coefficient and should be avoided, if possible.
2) Adequate fuel element - An adequate fuel element must be developed to withstand the neutron radiation. Severe metalurgical problems can be anticipated.
3) Transportation and reprocessing of fuel - Fuel elements for the LMFBR will be more radioactive at the time of processing and handling than present fuel elements due to higher specific power, higher total irradiation, and shorter cooling times of spent fuel (to decrease carrying charges on capital investment). This greater radioactivity will require better thermal cooling during shipping and greater safeguards against shipping accidents.
4) Sodium handling - Because sodium reacts violently with air and water, leakage prevention from the cooling system is essential. Also, sodium opaqueness requires fueling to be carried out blind.
5) Plutonium - The LMFBR uses plutonium for fuel. Because plutonium is easily processed for use in nuclear weapons, theft becomes a possibility, increasing transportation and handling security risks.

Whereas the above problem areas are challenging, there is no indication that they cannot be solved. Experimental plants are already operating in the U.S. and in foreign countries. The high interest in the development of this concept together with the expenditures being made indicate a most certain development future despite controversy over safety and security problems. Implementation obstacles to overcome include raising sufficient development funds, site selection, licensing, safety and security.

5. Liquid Metal MHD/Steam Binary Plant

The key areas which require research and development to validate performance predictions and establish the feasibility of long life for liquid metal MHD topping plants are:

1) Experimental verification of performance of an LMMHD generator with a cesium-lithium mixture.
2) Performance verification of advanced separator concepts at lower void fractions and dynamic load than for a single stage (space) system.
3) Validation of corrosion resistance of Haynes 25 and other super alloys in a high velocity two-phase mixture of cesium vapor with lithium droplets, and in low velocity lithium.
4) Compatibility of Haynes 25 or other super-alloys with refractory metal components and/or coating in a dynamic liquid metal system.
5) Furnace design and evaluation of fireside corrosion in the LMMHD furnace at the required temperature with alternate fuels.
6) Cesium condensor/steam boiler design.

In addition, liquid metal handling presents a potential safety problem. However, as discussed in Appendix E, appropriate designs and safety precautions can prevent catastrophic failures. The progress on the above problem areas is as follows (see Appendix E for details).

Efficiency calculations have been based on component hydraulic experiments and are believed to be accurate (see Appendixes C, D and E). Data to verify LMMHD generator performance (and thus system efficiency) could be obtained in 4-5 years with a 5 MW test system if funding of about $1.5 million per year were provided. If the funding were increased even more, the minimum time to accomplish the technology demonstration would be about two years.

Verification of separator performance should be resolved in the first year of the development program. The materials problems could be resolved in the first 2-3 years. The remainder of the program would be system tests of the 5 MW (input) LMMHD system.

Of all the systems considered, LMMHD is the least developed. However, it has received funding in terms of one or two orders of magnitude less than other advanced systems. If LMMHD would receive future funding comparable to other advanced concepts, it could very likely have comparable technological status.

G. RELIABILITY, MAINTAINABILITY, AND SAFETY

It was not possible in this study to conduct detailed studies of reliability, maintainability, and safety. The following general statements can be made, however, regarding LMMHD characteristics in these three categories.

Reliability: The LMMHD system is very simple, requiring no moving parts. This suggests high inherent reliability. Its high temperature of operation, however, requires system demonstration with economically viable materials, and long-term-operations needs to be proven.

Maintainability: The primary factors affecting maintainability will be erosion and deposition within the ducting and operations related to liquid metal handling. Erosion rates have been audited and found to be quite low, requiring little maintenance. The maintenance requirements due to liquid metal handling, periodic servicing and inspection of the system, etc., must be established in the future as the LMMHD system becomes better defined.

Safety: The primary safety hazard inherent with LMMHD is its use of liquid metals at high temperatures. Liquid metal loops have been operated successfully, however, in numerous cases. High-temperature (> 2000°F) lithium systems have been built and operated for time periods to 10,000 hours. Personnel and equipment hazards are similar to those faced by the liquid metal fast-breeder reactor development, except that there is no radioactivity hazard.

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